Fabrication and Characterization of Linear and Nonlinear Photonic Devices in Fused Silica by Femtosecond Laser Writing

by

Jason Clement Ng

A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
Graduate Department of The Edward S. Rogers Sr.
Department of Electrical and Computer Engineering
University of Toronto

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Abstract

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Femtosecond laser processing is a flexible, three-dimensional (3D) fabrication technique used to make integrated low-loss photonic devices in fused silica. My work expanded the suite of available optical devices through the design and optimization of linear optical components such as low-loss (<0.5 dB) curved waveguides, directional couplers (DCs), and Mach-Zehnder interferometers (MZIs). The robustness and consistency of this maturing fabrication process was also reinforced through the scalable design and integration of a more complex, multi-component flat-top interleaver over a wide >70-nm spectral window.

My work further complemented femtosecond laser processing with the development of nonlinear device capabilities. While thermal poling is a well known process, significant challenges had restricted the development of nonlinear devices in fused silica. The laser writing process would erase the induced nonlinearity (erasing) while a written waveguide core acted as a barrier to the thermal poling process (blocking). Using second harmonic (SH) microscopy, the effectiveness of thermal poling on laser-written waveguides was systematically analyzed leading to the technique of “double poling”, which effectively overcomes the two challenges of erasing and blocking. In this new process,
the substrate is poled before and after waveguide writing to restore the induced non-
linearity within the vicinity of the waveguide to enable effective poling for inducing a
second-order nonlinearity (SON) in fused silica. A new flexible, femtosecond laser based
erasure process was also developed to enable quasi-phase matching and to form arbitrarily
chirped gratings. Following this result, second harmonic generation (SHG) in a quasi-
phase-matched (QPM) femtosecond laser written waveguide device was demonstrated.
SHG in a chirped QPM structure was also demonstrated to illustrate the flexibility of
the femtosecond laser writing technique. These are the first demonstration of frequency
doubling in an all-femtosecond-laser-written structure. A maximum SHG conversion ef-
ficiency of $1.3 \pm 0.1 \times 10^{-11}/\text{W-cm}^{-2}$ was achieved for the fundamental wavelength of
1552.8 nm with a phase-matching bandwidth of 4.4 nm for a 10.0-mm-long waveguide.
For a shorter sample, an effective SON of $\chi(2) = 0.020 \pm 0.002 \text{ pm/V}$ was measured.

The results collectively demonstrate the versatility of femtosecond laser additive and
subtractive fabrication and opens up the development of integrated nonlinear applications
and photonic devices for future lab-on-a-chip and lab-in-a-fiber devices.
Dedication

To Maggie, my wife, and to my Lord and Saviour, Jesus Christ
Acknowledgements

As I conclude my long journey through the desert, I am extremely fortunate and grateful to have been supported by so many friends and family, without whom I would still be wandering. First, I would like to express my sincere gratitude to my co-supervisor Professor Li Qian for her kindness, patience, and mentorship, and for giving me the opportunity to pursue this PhD almost a decade ago and the encouragement to complete it. I am also very appreciative of my co-supervisor Professor Peter Herman for his continual optimism, close research guidance and enormous time investment throughout these years. I would also like to thank my supervisory committee, Professor Joyce Poon and Professor Stewart Aitchison for their time and constructive feedback.

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to North Toronto Chinese Baptist Church so many years ago, Lillian Won for inviting me to Thursday Bible Study Group, Christopher Lim for his personal mentorship, Melodie Lau for leading Masterlife, and Reverend Dr. Ted Tham for sharing his spiritual wisdom, encouragement, and joy.

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To my beautiful, loving wife, my better half, and the Moon of My Life, Dr. Maggie Fung, thank you. During those late, dark, and lonely nights in the lab, it was your love that kept me going. Thank you for marrying me three and a half years ago, for standing beside me, and for never giving up. I still feel like the luckiest man in the world and can’t wait to start a family together as we prepare for the birth of our first child. Thank you.

Finally, I would like to thank my Lord and Saviour Jesus Christ, who died for my sins and gave me eternal life, for I once was lost, but now am found.
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<tr>
<td>ACF</td>
<td>autocorrelation function</td>
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<td>ASE</td>
<td>amplified stimulated emission</td>
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<td>BGW</td>
<td>Bragg grating waveguide</td>
<td>x, 62, 63</td>
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<td>CMT</td>
<td>coupled mode theory</td>
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<td>DC</td>
<td>directional coupler</td>
<td>iii, viii, ix, 8, 9, 11, 39–46, 48, 72</td>
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<td>EO</td>
<td>electro-optic</td>
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<td>FTI</td>
<td>flat-top interleaver</td>
<td>ix, 9, 38, 41–48</td>
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<td>FWHM</td>
<td>full-width half-maximum</td>
<td>26, 67</td>
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<td>HF</td>
<td>hydrofluoric</td>
<td>viii, 12–14, 16, 30</td>
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<td>HWP</td>
<td>half-wave plate</td>
<td>26</td>
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<td>KOH</td>
<td>potassium hydroxide</td>
<td>30</td>
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<td>LBO</td>
<td>lithium triborate</td>
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<tr>
<td>LED</td>
<td>light-emitting diode</td>
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<tr>
<td>MZI</td>
<td>Mach-Zehnder interferometer</td>
<td>iii, ix, 8, 9, 30, 42–48, 71</td>
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<tr>
<td>NA</td>
<td>numerical aperture</td>
<td>38, 47, 61</td>
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<tr>
<td>OSA</td>
<td>optical spectrum analyzer</td>
<td>28, 62, 63</td>
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<tr>
<td>PLC</td>
<td>planar lightwave circuit</td>
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<td>QPM</td>
<td>quasi-phase-matching</td>
<td>iv, viii–x, 6–8, 21–25, 31, 58–63, 65, 67–69, 72</td>
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<td>SEM</td>
<td>scanning electron microscopy</td>
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<td>SH</td>
<td>second-harmonic</td>
<td>iii, viii–x, 6, 8, 9, 14–17, 19–21, 32–36, 49–57, 59–61, 71, 72</td>
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<td>SHG</td>
<td>second-harmonic generation</td>
<td>iv, viii–x, 7–9, 14, 17–21, 23, 24, 32, 33, 58, 59, 62–65, 67–69, 71</td>
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<td>SON</td>
<td>second-order nonlinearity</td>
<td>iv, viii, x, 5, 9, 12–17, 24, 29, 50, 56, 60, 69, 71, 72</td>
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<td>SPDC</td>
<td>spontaneous parametric down-conversion</td>
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<td>WDM</td>
<td>wavelength division multiplexer</td>
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Chapter 1

Introduction

Femtosecond laser processing has been maturing for the last two decades as a method for fabricating optical waveguides and integrated optical circuits in fused silica [1]. Fused silica is both a low-cost and high transparency medium exhibiting low loss across a wide spectrum, which is why silica is a desirable platform for integrated optical circuits [2, 3]. While high density silica-on-silicon planar lightwave circuit (PLC) has been a popular method for fabricating a range of on-chip waveguides and devices [4–6], this alternate process requires more complex masking procedures and fabrication within a cleanroom environment. In contrast, photonic circuits written with femtosecond lasers can be more rapidly prototyped in a single-step process, without these additional requirements [7]. Waveguides and circuits can be written in a matter of hours or even minutes, which enables short fabrication cycles. Femtosecond laser processing is also an intrinsically three-dimensional (3D) process capable of fabricating 3D circuits in novel geometries [8, 9]. Its flexibility also enables the simple integration of multiple 3D photonic devices into single transparent substrates [3, 10, 11]. Finally, low-index contrast glass waveguide written with femtosecond laser waveguides benefit from high coupling efficiency with fiber systems and high photon extraction efficiency, which makes them practical for exploring quantum photonic devices and concepts [7]. The combination of all these benefits make femtosecond laser processing an attractive method for the lithographic fabrication of
optical circuits for a range of applications, for example, microvalves [12], micropumps [13] for manipulating single cells for biomedical applications [14–16] and photonic quantum circuits for quantum applications [7,17,18].

1.1 Overview of Femtosecond Laser Processing

1.1.1 Femtosecond Laser Writing

A variety of passive optical devices have been previously fabricated including waveguides [1,19], power splitters [20], directional couplers [21], polarization splitters [22] and Bragg gratings [23]. For example, Fig. 1.1 shows a Y-splitter written into a bulk sample of fused silica lit up by 514.5-nm light, where the waveguide is outlined by the scattering of the confined light.

A more advanced function is based on directional couplers (DCs), shown schematically in Fig. 1.2, which offers flexible power splitting ratios and spectral control. The work shown in Fig. 1.3 further extends simple power splitting into a polarization splitter providing almost 20-dB of contrast between the two output arms. Bragg grating waveguides have also been fabricated to provide selective spectral reflections. An example of one fabricated using periodic modulation during waveguide writing is shown in Fig. 1.4.

The integration of laser written optical components into functional optical microsystems presents a formidable challenge, owing to high waveguide loss together with limited

Figure 1.1: Femtosecond laser written power splitter in fused silica. Image reproduced from [20] © 1999 Optical Society of America
1.1. Overview of Femtosecond Laser Processing

process control to compensate for wavelength dependence, dispersion, phase offsets, and birefringence. Unlike the advanced design and manufacturing finesse available in today’s PLC engineering, femtosecond laser writing poses its own unique challenges in managing optical loss in variously directed waveguide paths and in controlling waveguide mode size

Figure 1.2: Schematic layout of a femtosecond laser written directional coupler in fused silica. Image reproduced from [21] © 2001 Optical Society of America

Figure 1.3: Output power and mode profile (top) for a femtosecond laser written polarization splitter plotted as a function of input polarization. Image reproduced from [22] © 2011 Optical Society of America
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Figure 1.4: Reflection spectra of a femtosecond laser written Bragg grating waveguide based on periodic modulation during waveguide writing. Image reproduced from [23] © 2006 The Institute of Engineering and Technology

and birefringence through a myriad of laser exposure parameters such as pulse duration, polarization [24], focusing power, or pulse front tilt [25] that collectively drive a unique material response. Accurate modelling design and control is needed to balance trade-offs between loss, component size, and process variability to form highly functional integrated multi-component photonic systems.

As photonic circuits become more integrated and compact, many groups today are pursuing 3D integration strategies. For example, specific device applications such as a fluorescence excitation and detection in a lab-on-a-chip device has been used as a biomedical sensor as shown in Fig. 1.5 [26]. The optical waveguide, not visible due to low index contrast, delivered 532 nm light to excite the fluorescence within a microfluidic channel with high spatial selectivity. Also, quantum circuits have also been designed and developed for quantum photonics as the components required for scalable quantum computation have already been produced [7]. An example of a femtosecond-laser written circuit embedded within a larger quantum circuit for measuring a Hong-Ou-Mandel interference dip for three photons is shown in Fig. 1.6 [17], where a DC is used as a beamsplitter to demonstrate a Hong-Ou-Mandel interference dip for three photons.
1.1. Overview of Femtosecond Laser Processing

Figure 1.5: Lab-on-a-chip sensor using laser-induced fluorescence to detect labelled molecules with high spatial selectivity. The waveguide is not visible, but marked, due to the low refractive index contrast. Image reproduced from [26] © 2009 The Royal Society of Chemistry

Figure 1.6: Femtosecond laser written quantum circuit demonstrating quantum interference. (a) Measurement setup with femtosecond laser written DC integrated with fiber system. (b) Generalized Hong-Ou-Mandel interference dip observed for the context in (a) for three photons. Image reproduced from [17] © 2009 Optical Society of America

1.1.2 Extension to Nonlinear Applications

A significant unexplored opportunity for development is the extension of femtosecond laser processing to nonlinear optical applications. Generally, there have been limited nonlinear all-optical functions demonstrated in fused silica, due to its weak optical non-
Figure 1.7: Active waveguide laser cavity built from a femtosecond laser written waveguide in an active material. Fiber components were integrated to couple light into the laser written waveguide. LD: laser diode; R: reflectivity. Image reproduced from [28] © 2004 Optical Society of America

linearity and the short interaction length afforded by integrated optical devices. As a result, many nonlinear applications have instead been more actively pursued in laser-structured active media or integrations with fiber systems in order to produce more sophisticated devices such as optical amplifiers [27] and lasers [28]. For example, a femtosecond laser process was used to write a waveguide in an active material and integrated with fiber components to form a laser cavity as shown in Fig. 1.7.

Fortunately, thermal poling is known to induce a sizable second-order nonlinearity (SON) within bulk fused silica. As much as 1 pm/V of induced nonlinear susceptibility, $\chi^{(2)}$, was reported [30], followed by a demonstration of poled gratings [29]. In Fig. 1.8, a

Figure 1.8: SH signal recorded from a poled grating in fused silica while scanning a Nd:YAG pump beam (1064 nm) across the sample. Labels indicate beam positions: Outside the grating (a), on a grating line (b) and (d), in between two lines (c). Image reproduced from [29] © 2002 American Institute of Physics
1.1. Overview of Femtosecond Laser Processing

Figure 1.9: EO-shift demonstrated in an integrated MZI-based EO modulator. An average 1 nm shift was observed from the application of 400 V across the electrodes of the EO modulator. Image reproduced from [31] © 2006 Optical Society of America

clear 2:1 contrast in the second-harmonic generation (SHG) signal strength was observed between the poled grating lines and the region between grating lines. An electro-optic (EO) modulator was also fabricated using a Mach-Zehnder interferometer (MZI) written with a femtosecond laser and thermally poled before patterned with gold electrodes using sputter coating. The spectral response is shown in Fig. 1.9 [31], where an average 1 nm spectral shift was observed upon applying a voltage of 400 V across the electrodes, representing a 20° phase shift in the output spectrum. The nonlinearity induced by thermal poling was estimated to be $\chi^{(2)} \sim 0.25$ pm/V.

Further investigations into the physical interactions between poling and femtosecond laser writing have also been conducted [32]. In thermally poled fused silica, a frozen DC field interacts with fused silica’s third-order nonlinearity to produce an effective SON [33], which can lead to nonlinear frequency conversion over a much shorter distance. This third-order nonlinearity can be 2-3 orders of magnitude larger than that of four-wave-mixing processes [34].

A nonlinear response alone is not sufficient for efficient frequency conversion, and quasi-phase-matching (QPM) is often employed alongside thermal poling to phase-match
Chapter 1. Introduction

nonlinear interactions over long interaction lengths, such as in poled fibers. In this process, the entire length is first thermally poled uniformly and then periodic erasing of the induced nonlinearity is applied, often using UV mask erasure [35], or continuous point erasure [36]. In 2009, Li et al. used e-beam deposition, and an additional photolithographic step to perform limited QPM SHG on a femtosecond laser written waveguide. Despite applying temperature tuning, the device could not achieve perfect phase matching at the operating wavelength, leaving a residual phase mismatch of $\Delta kL = 3\pi$, far detuned from perfect phase-matching [37], possibly because of process variability. The opportunity remains to use femtosecond laser fabrication to perform perfect phase-matching and perform QPM by leveraging the rapid prototyping advantages afforded by this process. By developing effective nonlinear components in fused silica, additional functions such as frequency conversion can be integrated into future optical photonic circuits in fused silica. For example, entangled photons can be generated through SHG or spontaneous parametric down-conversion (SPDC) and manipulated through DCs and MZIs to perform quantum experiments.

1.2 Thesis Objectives

This thesis advances the development of femtosecond laser processing through the design and fabrication of linear and nonlinear optical components and circuits for the integration of future optical circuit and lab-on-a-chip applications. To achieve this goal, a series of new processes and techniques have been developed to address the following challenges to femtosecond laser processing in fused silica:

1. Integrate multiple components onto a single compact chip device through the precise design and control of multiple DCs and MZIs into a flat-top interleaver.
2. Induce and characterize an effective $\chi^{(2)}$ nonlinearity within the femtosecond laser written waveguide in fused silica substrate using a double poling technique and SH microscope to improve overlap of poling zones with waveguides.

3. Demonstrate the feasibility of fabricating a nonlinear component written and fabricated using femtosecond laser processing techniques to generate SHG from a QPM waveguide.

### 1.3 Chapter-by-Chapter Outline

The following is a chapter-by-chapter summary:

Chapter 2 (Background) provides a review of the major concepts and physical processes leading up to the fabrication of nonlinear devices using femtosecond laser processing. This includes femtosecond laser writing, thermal poling, and QPM.

Chapter 3 (Experimental Systems and Procedures) discusses the experimental systems, apparatus, and procedures that were built and developed in order to perform the experimental work. Specifically, the physical apparatus and procedures related to the femtosecond laser, optical waveguide characterization, thermal poling, and SH microscopy systems are described.

Chapter 4 (Linear Optical Components) presents the simple linear optical components that were designed and fabricated using femtosecond laser writing. Devices and characteristics that are discussed include waveguides, DCs, MZIs, and an integrated flat-top interleaver (FTI).

Chapter 5 (Thermal Poling of Waveguides in Fused Silica) presents the development and integration of thermal poling as a method for inducing SON within femtosecond laser
written waveguides. Various approaches for performing the thermal poling via different electrode geometries are presented in addition to the description of experimental equipment used to fabricate and visualize the induced nonlinearity using SH microscopy.

Chapter 6 (SHG in Femtosecond Laser Written Waveguides) details the experimental results from a QPM waveguide demonstrating effective SHG. A new method for performing erasure using femtosecond laser techniques is included.

Chapter 7 (Conclusions and Future Work) discusses a summary of the present work and avenues for future development.
Chapter 2

Background

2.1 Femtosecond Laser Processing

Femtosecond laser processing is a fast, flexible, three-dimensional (3D) method for creating optical devices in transparent media [3]. Since the Davis et al. demonstration of writing waveguide in glass [1], femtosecond lasers have been used to create waveguides and other more complex optical circuits in a variety of media including borosilicate glasses [1–3] and fused silica glass [2] either in bulk substrates, and more recently in fiber [38]. Typically, the fabrication of these optical devices involve focusing the femtosecond laser within the transparent media to induce a phase or structural modification within the glass [3,39] through nonlinear absorption. The electric field strength of these pulses are typically on the order of $10^9$ V/m, which corresponds to laser intensities of $5 \times 10^{20}$ W/m$^2$ [40]. Translation stages are used to control the relative focus position in 3D within the substrate and at specific power levels, scan speeds, repetition rates, and polarizations to form localized, higher refractive index zones ($\sim$0.01-0.035 [1]) within volumes as small as 0.008 µm$^3$ [41] to permit low loss waveguiding through the transparent media. In 2005, Eaton et al. varied laser exposure parameters to create 0.2-dB/cm propagation loss waveguides in Schott AF45 glass. Images of these waveguides and guiding mode profiles are shown in Fig. 2.1.
Chapter 2. Background

Figure 2.1: Microscope images and mode profile of femtosecond laser written waveguide. Left: Cross-section, Middle: Transverse, Right: Mode profile at 1550 nm wavelength. Image reproduced from [2] © 2005 Optical Society of America

![Figure 2.1](image1.png)

Figure 2.2: Schematic and near-field coupler output from a femtosecond laser written 3D DC. (a) Schematic of the 3D coupler, (b) monochromatic CCD image of the coupler output for a 632.8 nm He-Ne laser input in one waveguide on the input side, and (c) colour CCD camera image from a broadband light source. Image reproduced from [42] © 2003 Optical Society of America

![Figure 2.2](image2.png)

By changing the shape of the waveguides, 3D arcs and bends have been used to create 3D DCs [21, 42, 43]. In one such demonstration of a 3D coupler, an single input is split into three separate output arms, which has been visualized in Fig. 2.2. Femtosecond laser
written couplers have also been applied as optical power splitters [44], polarization beam splitters [22], and rotated waveplates for quantum state tomography [45, 46]. Bragg grating waveguides have also been created with femtosecond laser processing [47, 48], which has been used to create a variety of sensors [49–51].

In addition to waveguiding, femtosecond laser processing has been found to create self-organized nanogratings within bulk fused silica [53]. By controlling the polarization of the input laser, different orientations of nanogratings can be achieved. When polarized parallel to the scan direction, nanoplanes become aligned perpendicular to the scan direction, and vice versa for the writing polarization perpendicular to the scan direction. These nanoplanes are revealed from SEM analysis after 20 minutes of etching in 0.5% HF acid as shown in Fig. 2.3 [54]. While the former case provides for lower loss waveguides,
the latter case enables selective, more efficient etching when submerged in HF acid as shown in Fig. 2.4 [52].

The selective, chemical etching of these structures using HF or potassium hydroxide (KOH) created by femtosecond laser exposure has been used to fabricate high-aspect ratio microfluidic microstructures in fused silica substrates [55, 56]. Through a volume sampling method, 3D patterns with smooth walls can be etched out [57]. Controlling the laser polarization, and thus nanoplanes, allow single step laser writing processes to write structures that effectively guide light and structures that etch out after chemical etching. Microfluidic sensors have been demonstrated to sense the index of medium within the microfluidic channels fabricated within 2 µm of Bragg gratings waveguides [58]. Also, optical resonator arrays have been fabricated within fibers to serve as refractive index sensors [59]. Other applications such as 3D microfluidic mixers [60] and single

![Figure 2.4](image)

**Figure 2.4:** Selective HF etching of nanograting tracks by variable pulse energy and polarization of a femtosecond laser exposure of fused silica. Laser tracks were written with polarizations parallel (top), at 45° (middle), and perpendicular (bottom) to the scan direction for each pulse energy. In all cases, the perpendicular polarization yielded nanogratings that facilitated selective etching of the laser tracks by HF etching. Image reproduced from [52] © 2005 Optical Society of America
2.2 Thermal Poling

Thermal poling is a process where an internal electric field is frozen into a centrosymmetric media, typically bulk glass or glass fiber, to break the inversion symmetry of the material. This frozen-in field, $E_{DC}$, combines with the intrinsic third order nonlinearity, $\chi^{(3)}$ to induce an effective second-order nonlinearity (SON), $\chi_{\text{eff}}^{(2)}$, according to $\chi_{\text{eff}}^{(2)} = 3 \chi^{(3)} E_{DC}$, which had been confirmed by comparing the tensor geometry between $\chi_{\text{eff}}^{(2)}$ and $\chi^{(3)}$ [33]. This new induced SON can then enhances the optical nonlinearity of the medium for various nonlinear applications. Effective $\chi^{(2)}$ nonlinearities as high as 1 pm/V has been achieved in bulk glass [30], and as high as 0.1 pm/V in periodically poled fused silica fiber [63].

The typical process for thermal poling involves: (1) Heating the substrate above to increase ion mobility, (2) applying an external high voltage across the medium to redistribute the internal ions, (3) cooling the substrate back to near room temperature, before finally (4) removing the high voltage. During the first phase, the substrate was heated up to 280 – 320°C to increase the mobility of ions, which become aligned to the external field in the second phase. After cooling, the external voltage is removed and the displaced ions are frozen into its new position to form a permanent internal DC electric field aligned with the original poling field [31,64,65].

The SON induced by thermal poling has been measured and visualized through a variety of methods. The Maker fringe technique is one traditional method for measuring the strength and profile of the nonlinearity by recording generated second-harmonic (SH) power against the incident angle of a pump beam, yielding the Maker fringes shown in Fig 2.5 [66]. The induced nonlinearity can also be revealed using HF acid etching, a destructive technique where the ion depletion zone is selectively etched in comparison to
Figure 2.5:  Experimental Maker Fringe curve for measuring induced nonlinearity in poled fused silica. Image reproduced from [66] © 2003 IEEE

other parts of the glass [67]. An example is shown in Fig. 2.6, where the poled region around the anode was selectively etched faster than the rest of the fiber cross-section.

More recently, SH microscopy has been utilized as a direct and non-destructive method for visualizing the poling nonlinearity [32,64]. In this process, a laser pump beam is focused into a transparent medium to generate second-harmonic generation (SHG), a

Figure 2.6:  Visualization of the second-order nonlinearity in twin-holed fiber. HF acid was used to reveal an induced SON layer $\sim 10$ $\mu$m below the anode surface. Image reproduced from [67] © 2009 Optical Society of America
2.2. Thermal Poling

Figure 2.7: SH images visualizing the SON in poled bulk fused silica. The induced SON was localized in a narrow layer $\sim$9.4 $\mu$m beneath the anode surface. (a) Ordinary transmission image. (b) SH image. (c) Overlay image of the ordinary transmission and SH images. Image reproduced from [32] © 2008 American Institute of Physics

second-order process, only from regions where a SON has been induced. The SH signal is recorded into two-dimensional (2D) micrographs at high ($\sim$1 $\mu$m) resolutions limited only by the laser focal spot as shown in Fig. 2.7 [32]. In this example, ordinary transmission images and SH images are measured independently before being overlaid into a single image to show the location of the induced nonlinearity. Line scans of the sample cross-section can also be performed to reveal the SON profile as shown in Fig. 2.8 [8], where a line scan measurement of the SON profile was taken through the poling zone.

Figure 2.8: Line scan measurement of the SON profile through the poling zone using SH microscopy. Image reproduced from [8] © 2009 Higher Education Press and Springer-Verlag
From these visualization techniques, the majority of the poling nonlinearity has been observed to be localized within 8-14 µm of the anode, to form an ion depletion zone. For example, the HF etching method in a double poled fiber revealed a \( \sim 10 \) µm depletion zone in Fig. 2.6. The SH profile in Fig. 2.7 revealed a \( \sim 9.4 \) µm depletion zone in bulk glass [31,32,67].

Additional experiments with twin-hole fiber have confirmed successful poling without a cathode [67]. The migration of ions have been modelled and Na\(^+\) ions were identified as the primary charge carrier responsible for the ion depletion zone as Na\(^+\) ions are pushed away from the surface over the first 30-100 minutes. Over longer time scales, H\(^+\) ions were suggested to play a role as well [68].

Recently, the effect of thermal poling on femtosecond laser writing has also been investigated with SH microscopy. While laser processing is known to erase the effects of thermal poling [69], An et al. observed that the modified structure created by laser waveguide writing contributes to a blocking effect that hinders thermal poling for certain glasses, such as a fused silica [32]. Higher resolution imaging of the laser modified region has revealed nanogratings and nanoplanes which may be responsible for hindering charge migration [70]. Since these findings, the effectiveness of nonlinear functions based on femtosecond laser processing has been limited to other media, such as boro-aluminasilicate glass [71,72], and lithium niobate [73], which have been typically known to be higher loss devices.

### 2.3 Second Harmonic Generation

SHG is a nonlinear optical process first demonstrated by Franken et al. in 1961 [74] whereby a pump wave at the fundamental frequency, \( \omega \), was converted into the second harmonic frequency at \( 2\omega \) through the interaction with a nonlinear material [75]. In nonlinear optics, the pump wavelength interacts with the nonlinear medium to create a
2.3. Second Harmonic Generation

nonlinear polarization field, $P_{NL}$, at new frequencies. The second order component of this nonlinear polarization, $P^{(2)}_{2\omega}$, is given by:

$$P^{(2)}_{2\omega} = \epsilon_0 \chi^{(2)}_{\text{eff}} E_{\omega}^2,$$

(2.1)

where $\epsilon_0$ is the permittivity of free space, $\chi^{(2)}_{\text{eff}}$ is the second order nonlinear susceptibility that describes the degree of the second order polarization of a dielectric material in response to an applied electric field, and $E_{\omega}$ is the electric field of the fundamental wave.

Assuming negligible loss and a slowly varying envelope approximation for a simple plane wave of amplitude, $E_{\omega}$, travelling in the $z$-direction yields the following coupled wave equations for SHG:

$$\frac{\partial E_{\omega}}{\partial z} = -\frac{i \omega}{2n_{\omega}c} \chi^{(2)}_{\text{eff}} E_{2\omega}^* E_{\omega} e^{-i \Delta k z},$$

(2.2)

$$\frac{\partial E_{2\omega}}{\partial z} = -\frac{i \omega}{2n_{2\omega}c} \chi^{(2)}_{\text{eff}} E_{\omega}^2 e^{i \Delta k z},$$

(2.3)

where $*$ denotes a complex conjugate, $n_{2\omega}$ is the index of refraction for the second harmonic and $\Delta k$ is the phase mismatch between the interacting waves given by:

$$\Delta k = k_{2\omega} - 2k_{\omega}.$$  

(2.4)

In the case of weak conversion efficiency and negligible pump depletion, where the electric field amplitude of the fundamental wave, $E_{\omega}$, can be assumed to be constant, the following solution is obtained for the generated harmonic field after propagating through a nonlinear medium of length, $L$:

$$E_{2\omega} = -\frac{i \omega \chi^{(2)}_{\text{eff}}}{2n_{2\omega}c} E_{\omega}^2 L \frac{\sin(\Delta k L/2)}{\Delta k L/2} e^{i \Delta k L/2}.$$  

(2.5)
From the above, a conversion efficiency, \( \eta_{2\omega} \), is more conveniently derived for the SHG, which can be obtained from the ratio of the second harmonic and fundamental powers, \( P_{2\omega} \) and \( P_{\omega} \), respectively:

\[
\eta_{2\omega} = \frac{P_{2\omega}}{P_{\omega}} = \eta_{0,2\omega} \frac{\sin^2(\Delta k L/2)}{(\Delta k L/2)^2}
\]

(2.6)

where \( \eta_{0,2\omega} \) is the optimum SHG conversion efficiency in the case of perfect phase-matching, which is given by:

\[
\eta_{0,2\omega} = \frac{2\pi^2 \chi^{(2)}_{\text{eff}} L^2 I_{\omega}}{\epsilon_0 n_{2\omega}^2 n_{\omega} c \lambda_{\omega}^2},
\]

(2.7)

where \( I_{\omega} \) is the fundamental pump intensity, \( c \) is the speed of light, and \( \lambda_{\omega} \) is the fundamental wavelength. The phase mismatch, \( \Delta k \), results from the unequal phase velocities between the fundamental and accumulating SH waves propagating through the medium while the \( \text{sinc}^2 \) response results from the rectangular poling region. The larger the phase mismatch, the greater the reduction in peak conversion efficiency.

Further introducing the effect of propagation loss in the waveguides through linear absorption terms yields the following modified conversion efficiency, \( \eta_{\alpha,2\omega} \) [75]:

\[
\eta_{\alpha,2\omega} = \eta_{0,2\omega} \exp\left[-(\alpha_{\omega} + \alpha_{2\omega}/2)/L\right] \frac{\sin^2(\Delta k L/2) + \sinh^2[(\alpha_{\omega} - \alpha_{2\omega}/2)L/2]}{(\Delta k L/2)^2 + [(\alpha_{\omega} - \alpha_{2\omega}/2)L/2]^2}.
\]

(2.8)

where \( \alpha_{\omega} \) and \( \alpha_{2\omega} \) are the absorption coefficients for the fundamental and SH wavelength, respectively. Conversion efficiencies with various levels of absorption loss is shown as a function of phase mismatch in Fig. 2.9. In addition to a general decrease in conversion efficiency, as linear absorption increases to \( \alpha_{2\omega} L \geq 5 \), the phase-matching curve shifts from a \( \text{sinc}^2 \) function to a Lorentzian function.
2.3. Second Harmonic Generation

Figure 2.9: Normalized SHG frequency conversion efficiency with varying absorption, \( \alpha_{2\omega} \), at the SH frequency as a function of phase mismatch.

Figure 2.10: Normalized SH conversion efficiency as a function of position in a nonlinear medium for various values of phase mismatch.

From these phase-matching curves, the full-width half-maximum (FWHM) phase-matching bandwidth, \( \Delta k_{BW} \), for the lossless case is approximately [75]:

\[
\Delta k_{BW} = \frac{2.784}{L}. \tag{2.9}
\]
Similarly, the coherence length, $L_c$, the distance over which the constructive frequency conversion occurs, is defined by:

$$L_c = \frac{\pi}{|\Delta k|}$$

(2.10)

After propagating through a distance equal to this coherence length, the relative phase between the interacting waves become shifted by $\pi/2$, resulting in destructive interference of newly generated SH light against the prior generated SH light. Energy flows back to the fundamental, which is shown in Fig. 2.10 for various values of phase mismatch, $\Delta k L$. This coherence length is an important factor for determining and designing optimal lengths and thicknesses for nonlinear media for SHG, which is further explored in the next section on quasi-phase-matching (QPM).

### 2.4 Quasi-Phase-Matching

QPM is a method to engineer phase matching when it is not readily available from bulk materials using periodic modulation of the $\chi^{(2)}$ nonlinearity. First proposed independently in the 1960s by Bloembergen et al. [76] and Franken and Ward [77], QPM enables efficient nonlinear optical processes such as SHG and spontaneous parametric down-conversion (SPDC) by facilitating in-phase accumulation of the generated signals to maintain the relative phases between multiple interactive waves. This is often achieved by structurally adjusting the nonlinear medium at regular intervals, such as in periodically poled lithium niobate [78].

As described in Sec. 2.3, a difference in phase velocity between the fundamental and SH waves results in a relative phase change as the waves propagate through the medium. This phase mismatching causes the conversion efficiency to be reduced once the interaction length exceeds the coherence length, $L_c$, beyond which the SH energy
begins flowing back into the fundamental. With QPM, the nonlinear medium is adjusted periodically at period, $L_m$, an odd multiple of the coherence length according to:

$$L_m = mL_c = \frac{m\pi}{\Delta k}, \text{ for } m = 1, 3, 5, \ldots$$

(2.11)

where $m$ is the order of the QPM. This periodic adjustment either bypasses the domain where energy flow is reversed or introduces a $\pi$-phase shift in the medium to continue constructively transferring energy along the axis of propagation. One common method for performing QPM involves a simple stack of plates where each plate is one coherence length thick, with each consecutive plate inverted such that the nonlinear susceptibility is reversed in order to optimize the nonlinear process [79]. For QPM, the conversion efficiency for SHG in Eq. 2.6 is further adjusted for the new boundary conditions to yield a new optimum conversion efficiency, $\eta_{2\omega,QPM}$ [75]:

$$\eta_{2\omega}^0 = \eta_{2\omega,QPM} = \frac{2\pi^2 (2/m\pi)^2 \chi^{(2)}_\text{eff} (NL_c)^2 L_\omega}{\epsilon_0 n_\omega^2 n_{2\omega} c \lambda_\omega^2},$$

(2.12)

where $m$ is the order of the QPM and $N$ is the number of plates or uniform segments in the periodic medium. The conversion efficiency dependence on normalized gain length for various orders of QPM is shown in Fig. 2.11. While ideally, perfect phase-matching is desired, QPM media can compensate phase-matching simply by using multiple segments for much longer interaction lengths, which enables much larger conversion efficiencies.

In glass media, bulk substrates and silica fibers have been adapted to QPM via two-step, thermal poling and periodic erasure. The entire length is first thermally poled uniformly before erasing select regions, often using UV mask erasure [35,69], or continuous point erasure [36]. Periodic segments, or grating, of poled regions are left behind after erasure at pre-determined intervals corresponding to the desire phase matching period.

Using these methods, nonlinear processes such as SHG has been demonstrated in many materials since 1993, when Yamada et al. applied an external field at room temperature to periodically pole lithium niobate to obtain an SHG efficiency of 600%/W·cm².
for the fundamental wavelength of 851.7 nm [80]. Since then, periodically poled lithium niobate has become one of the most important examples of QPM due to its high efficiency (>40%) and excellent beam quality, which is used in many commercial products today [81, 82]. Some other examples of QPM include an all-fiber frequency doubled visible laser [63], and a source for entangled photon pair generation in twin-holed fiber for quantum communication applications [83].

2.5 Summary

Femtosecond laser processing continues to become more advanced as new devices continue to be developed using this intrinsically 3D, flexible, and versatile processing technology, especially for fused silica substrates where low loss waveguide formation is possible. An opportunity also exists for fabricating more complex circuits by integrating multiple components, which is currently lacking as most existing devices consist of very simple structures and geometries. By integrating thermal poling processes, the existing suite of

![Normalized SHG intensity as a function of position in perfectly phase matched, first order QPM, and third order QPM nonlinear media. Image reproduced from [75] © 2003 Marcel Dekker, Inc.](image)

**Figure 2.11:** Normalized SHG intensity as a function of position in perfectly phase matched, first order QPM, and third order QPM nonlinear media. Image reproduced from [75] © 2003 Marcel Dekker, Inc.
femtosecond laser written devices can be further extended to nonlinear optical functions, which can be made even more effective when advanced QPM techniques can be applied. The combination of femtosecond laser processing, thermal poling, and methods available to evaluate SH processes lays the foundation for the work presented in the following chapters. Opportunities for integrating complex integrated optical circuits extend the work of femtosecond laser writing in Chapter 4. The thermal poling process coupled with SH microscopy as a method to visualize this process enables the systematic investigation of the thermal poling of femtosecond laser waveguides in the results presented in Chapter 5. Finally, the principles of QPM is applied in Chapter 6 to demonstrate the possibilities for extending femtosecond laser writing to nonlinear optical functions.
Chapter 3

Experimental Systems and Procedures

A series of experimental processes and procedures were used and developed in order to fabricate the linear and nonlinear optical devices presented in this thesis. This chapter focuses on detailing the experimental equipment involved and the procedures that were developed and optimized during the course of this work.

3.1 Femtosecond Laser System

The femtosecond laser system formed the foundation of the research and was used to write waveguides in fused silica, prepare substrates for chemical etching, and finally to perform nonlinear erasure of induced nonlinearity for the quasi-phase-matching (QPM) work detailed in Chapter 6. A schematic of the existing femtosecond laser system is shown in Fig. 3.1. A femtosecond fibre laser (IMRA America, FCPA μJewel D-400-VR) was used as the source to provide \(~300\) fs laser pulses with pulse energies up to \(~1.3\) µJ at a wavelength of 1044 nm and repetition rate of 1 MHz. Additional specifications for the femtosecond laser are summarized in Table 3.1.
Figure 3.1: Schematic of IMRA femtosecond laser system.

After exiting the laser source, the beam’s power was controlled using a half-wave plate (HWP) and polarizer combination. A removable frequency doubling setup composed of an lithium triborate (LBO) crystal, pair of matched focusing and collimating lenses, and hot mirror for filtering out the pump beam, allowed for optional wavelength conversion to 522 nm. The polarization of the beam was controlled with a HWP before being focused into with an aspherical objective lens into transparent, fused silica substrates. Precise

Table 3.1: IMRA µJewel D-400-VR femtosecond fibre laser specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition rate</td>
<td>0.1–5 MHz</td>
</tr>
<tr>
<td>Centre wavelength</td>
<td>1045 nm</td>
</tr>
<tr>
<td>Emission bandwidth FWHM</td>
<td>&lt;10 nm</td>
</tr>
<tr>
<td>Polarization contrast ratio</td>
<td>&gt;20 dB</td>
</tr>
<tr>
<td>Pulse contrast ratio</td>
<td>38 dB</td>
</tr>
<tr>
<td>Pulse energy noise</td>
<td>&lt;5% rms</td>
</tr>
<tr>
<td>Output power stability</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>Beam quality, $M^2(X,Y)$</td>
<td>1.4, 1.3</td>
</tr>
<tr>
<td>Output beam diameter $(1/e^2)(X,Y)$</td>
<td>3.7 mm, 3.4 mm</td>
</tr>
<tr>
<td>Beam divergence $(X,Y)$</td>
<td>0.83 mrad, 0.55 mrad</td>
</tr>
<tr>
<td>Autocorrelation function (ACF) width</td>
<td>450 fs</td>
</tr>
</tbody>
</table>

*Provided by the manufacturer.
three-dimensional (3D) beam delivery was electronically controlled via translation stages (Aerotech ABL1000) that provided 2D, X-Y, control over the substrate platform and a 3rd axis of control, Z, via vertical adjustment of the objective lens. Software provided with the translation stages allowed commands and sequences to be coded in GCODE for automated processing. Additional details regarding the laser system have also been described in other theses [84,85].

3.2 Optical Waveguide Characterization System

The waveguides fabricated using the femtosecond laser system were subsequently evaluated with an optical waveguide characterization system to measure spectral loss, insertion loss, and mode profiles. This system provided straightforward interfacing with external light source and detection components via fiber coupled inputs and outputs. The glass substrates under test were placed on a 5-axis precision stage (Luminos I5000) that enabled precise micron-level control along three perpendicular axes as well two axes of rotation. Input and output probing stages on either side of the waveguides allowed a probe beam to be aligned and launched from one end and collected out from the opposite end, either via fiber or free space coupling, as shown in Fig. 3.2.

Fiber coupling was the simplest method for characterizing waveguides as cleaved tips of bare fiber (Corning SMF-28) were placed against one end of the waveguide. Index-matching oil was placed between the waveguide and fiber to minimize Fresnel reflection loss.

![Figure 3.2: Schematic of the optical waveguide characterization system. In this example, the input beam is polarization controlled in free space before being coupled into the waveguide under test, and fiber coupled out into the detection equipment. Index matching oil was placed between the waveguide and fiber to minimize Fresnel reflection loss.](image-url)
3.2. Optical Waveguide Characterization System

Matching oil ($n \sim 1.452$) was applied at the connection to eliminate the air gap between the interfaces and minimize Fresnel reflection loss. Free space coupling was used when precise polarization control was necessary for characterizing polarization-dependent responses. Various waveplates and polarizers were inserted into the free space path to obtain arbitrary input polarizations before focused into the waveguides under test. Free space out coupling was also used to measuring mode profiles as the diverging output was imaged with an aspherical lens and collected onto a CCD camera.

Initial alignment of the waveguides was performed with the aid of a red laser input ($\sim 632$ nm) and an overhead camera that provided real-time visualization of the coupled red light as it was scattered from the waveguide. The alignment was then improved by replacing the source with the source of a desired wavelength range and the power coupled through the system was optimized. A list of input sources and collection devices used in the present experiments are shown in Table 3.2.

### 3.2.1 Spectral Loss Measurement

Spectral insertion losses for the waveguides were typically measured using a broadband input source in conjunction with the optical spectrum analyzer (OSA). First, a baseline

<table>
<thead>
<tr>
<th>Device</th>
<th>Type</th>
<th>Operating Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadband ASE (Thorlabs ASE-FL7002)</td>
<td>Source</td>
<td>1530-1610</td>
</tr>
<tr>
<td>Edge-emitting LED (Agilent 83437A)</td>
<td>Source</td>
<td>1250-1700</td>
</tr>
<tr>
<td>Tunable laser (Photonetics Tunics-BT)</td>
<td>Source</td>
<td>1500-1600</td>
</tr>
<tr>
<td>Tunable fiber laser (Genia Photonics MOPA)</td>
<td>Source</td>
<td>1530-1560 (500 ps)</td>
</tr>
<tr>
<td>Erbium-doped fiber amplifier (PriTel FA-22)</td>
<td>Amplifier</td>
<td>1500-1600</td>
</tr>
<tr>
<td>Optical Spectrum Analyzer (Ando AQ6317B)</td>
<td>Detector</td>
<td>600-1750</td>
</tr>
<tr>
<td>InGaAs Detector (Newport 818-IG)</td>
<td>Detector</td>
<td>800-1650</td>
</tr>
<tr>
<td>Silicon Detector (Newport 818-IR)</td>
<td>Detector</td>
<td>400-1100</td>
</tr>
</tbody>
</table>
spectrum without the sample was recorded with the OSA to capture the spectral profile of the source and apparatus. Next, the sample was aligned and coupled into the system before a second spectrum was recorded. Typically, multiple laser waveguides were tested in sequence, and the baseline recorded again at the end of all measurements to ensure the source spectrum has not shifted by more than 2%. The difference between the measured waveguide transmission, $P_{WG}$, and the baseline, $P_{Ref}$, was attributed to the waveguide insertion losses, $IL$, given in dB by $IL = 10 \log\left[\frac{P_{WG}}{P_{Ref}}\right]$. 

3.2.2 Mode Profile Measurement

Mode profiles of the laser-formed waveguides were measured from the end facet of the silica block by collecting and collimating the diverging light in free space with a $15 \times$ microscope objective into a CCD camera. The measurement records the light intensity across the camera’s 2D sensor array. The laser input used for these measurements was typically a narrow bandwidth source tuned to the desired characterization wavelength. The size of the collected mode was calibrated against the known mode size of Corning SMF-28 fiber to determine the $1/e^2$ intensity mode sizes, known as mode field diameter (MFD), of the waveguide under test for the specific input wavelength.

3.3 Thermal Poling

A custom-built thermal poling system was used to induce second-order nonlinearity (SON) into the fused silica substrates, as shown in the schematic of the thermal poling apparatus in Fig. 3.3. This was accomplished by sandwiching glass substrates between two flat, polished stainless steel electrodes, where the bottom cathode also served as the substrate heater. The smaller anode was attached to small screw protruding upwards to interface with the electric circuit.

A high voltage circuit was built from a DC-DC amplifier capable of producing voltages up to 4 kV. In addition, a signal generator was amplified by an AC-AC amplifier and
Figure 3.3: Schematic of the thermal poling apparatus. The fused silica sample is sandwiched between two stainless steel electrodes, with the waveguides positioned closer to the smaller anode electrode. A strip heater was used as the cathode.

connected in series to provide an addition \( \sim 1 \) kV peak-to-peak signal, which was available for characterization purposes. A 1:1000 voltage tap was also built into the circuit and connected to an oscilloscope to monitor the output voltage. The heater circuit consisted of simple metal heating strip connected to a temperature feedback control system.

The thermal poling process consisted of first heating the sample to \( \sim 300^\circ C \) over the course of 10 minutes before turning on the high voltage of 3 kV across the sample. After 1 hour, the heater was turned off and fan-cooled to under 80\(^\circ\)C within 10 minutes before the high voltage was turned off.

3.4 Second-Harmonic Microscopy

Second-harmonic (SH) microscopy was used as a method for directly and nondestructively measuring the nonlinearity induced by the frozen-in DC electric field from the thermal poling process. To perform this, an entire SH microscopy system was designed and built around the femtosecond laser system described in Section 3.1 as the source. The collection part of the system consisted of a robust set of downstream optics fixed onto a rail system to image the 2D cross-section of the poled samples. The zones of \( \chi^{(2)} \) nonlinearity was imaged in the form of second-harmonic generation (SHG) signals at the high \( \sim 1 \) \( \mu \)m resolution of the focused laser beam. This two-step process involves first (1) preparing and packaging the glass substrates for characterization, and then (2) characterizing the
SHG in the samples with the scanning femtosecond laser source. The details of both these processes are described in the subsections below.

3.4.1 Sample Preparation for SH Microscopy

The poled waveguide samples were prepared for SH microscopy with the goal of exposing and revealing the substrate cross-sections for SH characterization. The poled waveguide samples were manually cleaved with a diamond scribe into \( \sim 2.5 \) mm wide sections and rotated to expose the substrate cross-sections vertically. Multiple test pieces were positioned side-by-side over a first layer of index-matched epoxy. Extra glass spacer pieces were placed around the samples to provide additional alignment support for the sample stack before adding more index-matched epoxy to the package. The stack was then sandwiched by two cover slips of 200 \( \mu \)m thickness to provide a uniform entry and exit surface for SH characterization. Index-matched UV epoxy was used to fill in air gaps and thus minimize aberrations and optimize image quality during SH characterization. Finally, the entire package was UV cured for \( \sim 2 \) minutes to permanently fix the pieces in place. A depiction of the cleaved sample before and after packaging is shown in Fig. 3.4.

3.4.2 SH Microscopy System

A custom SH microscopy collection system was designed and built to image 2D cross-sections of the packaged glass samples. Using the same IMRA femtosecond laser system shown earlier in Fig. 3.1 as the source, the fundamental pump at 1044-nm with the desired power and polarization was focused into the test samples. The forward scattered SHG was collected downstream from the \( \sim 1 \) \( \mu \)m diameter, \( \sim 6 \) \( \mu \)m deep laser focal volume as shown in Fig. 3.5. The downstream collection optics consisted of a series of optical components mounted onto a rail below the test sample. An objective lens was used to focus the signal into the 50 \( \mu \)m core of a multimode fiber and consisted of a 20\( \times \), 0.50 NA aspherical lens was fixed onto a 3-axis translation stage with manual rotation
3.4. Second-Harmonic Microscopy

Figure 3.4: Schematic of poled waveguide substrates packaged for SH microscopy. (a) Section of a cleaved sample with the waveguides aligned along the z-axis and cross section exposed in the xy-plane. The internal frozen-in field was oriented along the y-axis. (b) Sections of the cleaved sample were supported by extra glass spacer pieces and sandwiched between thin cover slips. The entire package was fixed using index-matched epoxy.

Figure 3.5: Schematic of the SH microscopy apparatus.
available along one axis. In between the objective lens and the fiber, a 45° dichroic mirror provided preliminary filtering by rejecting over 97% of the 1044 nm pump beam. Additional filtering of 1044 nm (OD4) was provided by a removable 520 nm wavelength, 28 nm wide bandpass filter. A 526 nm, 17 nm wide notch filter was also used to block the 522 nm signal for verification of the SH. The fiber output was connected to a fiber photon-counting system (Becker & Hickl SPC-830) previously established in the lab, and signals were synchronized to the translation stage position to assemble two-dimensional (2D), 256 × 256 pixel, raster scan images of the sample cross-sections of arbitrary sizes.

The focal volume of the input pump served to limit the spectral resolution of the microscope to ∼1 µm in the plane perpendicular to the beam, and ∼6 µm in the axis parallel to the beam. The image size, pixel dwell time, and scan time were variable, with the maximum image size limited by the travel range of the translation stage at over 10 cm × 10 cm and scan time scaling with the image size and collection duration. Typical scan times for 1 mm × 3 mm and 150 µm × 150 µm images took approximately 5 minutes and 2 minutes, respectively, to form a clear >60:1 contrast between regions of induced nonlinearity zones, and regular, unpoled zones.

The alignment procedure for the SH microscopy system consisted of working backwards from the multimode fiber, aligning the system for the expected SHG wavelength of 522 nm at the desired characterization depth. To capture the regions of interest within the packaged samples, a 2D raster scan was first performed over a large, 2-3 mm wide region before successively zooming into nonlinear regions near the surfaces. After the desired region was found, the system was realigned again to accommodate for small displacement errors caused by variations in the optical path length at different locations in the sample. Prior to data collection, the system was adjusted to the fundamental wavelength by applying a vertical offset to the microscope objective to account for the focal length mismatch caused by chromatic dispersion. The precise offset for the objective was verified through focus calibration against the sample surface.
A sample set of SH images collected using various combination of filters for a poled waveguide cross-section is shown in Fig. 3.6. Surfaces marked by arrows and waveguide features near the top anode surfaces were used to align the images against each other. The expected frozen-in DC field is marked in red. A microscope image is shown in Fig. 3.6(a) as the base image. Fig. 3.6(b) shows a low power (< 2 mW) linear transmission image from a 522 nm input, while Fig. 3.6(c) shows the SH image produced from the fundamental, 1044 nm laser source (15 mW) observed through a 520 nm bandpass filter. Replacing the bandpass filter with the notch filter for the same recording condition

![Figure 3.6: Waveguide cross-section of a poled sample under various illumination conditions were aligned using the anode-exposed glass surface (black arrows) and waveguide features, with the expected frozen-in DC field marked with red-arrows. (a) Image recorded with a white light microscope. (b) Image of 522 nm laser (< 2 mW) recorded with the SH characterization setup. (c) Image excited by 1044 nm laser source (15 mW) and recorded with the same SH characterization setup through a 520 nm wavelength, 28 nm wide bandpass filter. (d) Same as (c) with 520 nm bandpass filter replaced with 526 nm wavelength, 17 nm wide notch filter to confirm SH generation in the case of (c).](image)
reduced the SH signal to the near noise level of detection as seen in Fig. 3.6(d), confirming the SH generation in the anticipated ion-depletion zone. A weak (red) signal zone (left and right arrows) corresponding to laser-induced damage at the epoxy interface was observed near the edges where excessive laser exposure from multiple scans (>30) and increased dwell times due to deceleration effects of the translation stages caused burning of the epoxy and other artifacts.

The SH generation from this 12 μm thick poling zone was measured as a function of input laser polarization, which was controlled using a HWP, which yielding the SH signal (green) normalized to peak photon counts in Fig. 3.7. The peak SH signal coincides with alignment of the input laser polarization parallel to the internal DC field direction (0, π, 2π) as identified in Fig. 3.6, which corresponds to the stronger nonlinear tensor element, \( \chi^{(3)}_{iii} \). This stronger tensor element for fused silica is responsible for a 9:1 polarization dependence of SH generation favouring laser polarization aligned parallel with the frozen-in DC field [33]. A sinusoidal curve was a good representation of the observed oscillation,

![Graph showing polarization dependence](image)

**Figure 3.7:** Polarization dependence of transmitted signal through SH microscopy system. The signal strength of the 1044-nm (red) and frequency doubled 522-nm (green) light was collected while rotating the polarization of the 1044-nm input relative to the internal, frozen-in DC field.
yielding a smaller 3.7:1 contrast between the peak, parallel polarization condition to the minimum, cross-polarization condition. This oscillation fell short of the expected 9:1 contrast possibly due to sample alignment error ($\pm 5^\circ$) and high numerical aperture of the focusing beam leading to a background noise signal. In contrast, the linear transmission efficiency of the fundamental 1044-nm source (red) was nearly independent of input polarization, thus verifying that the SH signal originated from the thermal poling process.

3.5 Summary

In summary, various experimental systems were used and developed to fabricate and optimize femtosecond laser written devices. The femtosecond laser system and optical characterization systems were used to create, characterize, and optimize linear integrated circuits that are presented in the following chapter. A thermal poling and SH characterization system was developed to induce and image SON, which served as the tools necessary for enabling the subsequent work towards femtosecond laser written nonlinear devices.
Chapter 4

Linear Optical Components

This chapter presents a series of linear optical devices that have been designed and optimized to expand the suite of available devices for femtosecond laser writing. Simple components such as waveguides, directional couplers (DCs), and Mach-Zehnder interferometers (MZIs) were accurately modelled, fabricated, and characterized using standard transfer matrix models to form a foundation for the design and creation of more complex integrated circuits, such as a flat-top interleaver (FTI). The success of this FTI demonstrated the sufficient process accuracy and fabrication consistency for femtosecond laser writing of advanced optical circuits in three dimensions. These simpler linear components then also form a foundation on which to build in nonlinear devices presented in later chapters.

4.1 Femtosecond Laser Written Waveguides

Waveguides were written according to Section 3.1 in bulk fused silica with the IMRA femtosecond laser system and waveguides were characterized using the Luminos characterization system according to Section 3.2. Following the guidance of previous work [24], laser exposure parameters were optimized to values of 220 fs pulse duration, 1 MHz

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repetition rate, 120 nJ per pulse energy at 522 nm to provide low propagation and coupling loss to single mode fiber via mode size matching (10.4 µm mode field diameter at 1550 nm). The writing laser was focused to a depth of 100 µm below the glass surface with a 0.55 numerical aperture (NA) aspherical lens while air-bearing translations stages were used to control the glass slide motion relative to the focus position. Straight sections were scanned at 0.5 mm/s while curved sections defined by their radius of curvature, \( R \), were optimized to 0.3 mm/s to reduce bend loss.

Extrapolation of the loss data for sample lengths of 50.8, 25.4, and 12.7 mm to zero-length yielded an estimate of coupling losses that increased with wavelength, from 0.50 to 0.67 dB/facet over the 1250 to 1400 nm spectral range. Multiple waveguides with varying lengths of straight and curved sections (\( R = 35 \) mm and 75 mm) were fabricated to calculate the propagation loss, \( \alpha(R, \lambda) \) as shown in Fig. 4.1 across the 1250 to 1500 nm spectrum.

**Figure 4.1:** Propagation losses measured for the waveguides in the FTI compared against straight and curved waveguide losses. Losses for curved waveguides, including the FTI, increase exponentially with longer wavelength. The purple highlighted band at \( \sim \)1375 nm indicate losses due to OH defects [86].
In Fig. 4.1, straight waveguide losses decreased moderately from 0.93 to 0.37 dB/cm towards longer wavelength while bend losses rose nearly exponentially from 0.58 to 2.1 dB/cm for 75 mm radius waveguides and more steeply from 0.35 to over 8 dB/cm for 35 mm radius waveguides. While Rayleigh scattering is anticipated to account for the majority of loss in straight waveguides [87], the trend of increasing mode size with longer wavelength underpins the exponential-like increase seen in Fig. 4.1 for curved waveguides, following the expected trends of both infinite cladding models [88] and single-mode fiber bending loss [89] as the wavelength-to-bend ratio increases. However, overall losses are much higher here than found in planar lightwave circuits due to a three-fold weaker induced index contrasts of $\Delta n \sim 0.01$ [90] and overall roughness in the waveguide morphology generated by femtosecond laser interactions. An apparently anomalous trend in propagation loss, decreasing from 0.93 dB/cm for straight waveguides to 0.35 dB/cm for the smallest radius waveguide, arises when narrowed modes within bend regions shift partially outside the index modification zone to reduce optical scattering [89].

### 4.2 Directional Couplers

DCs are components that were evanescently coupled to transfer power from one waveguide to another. The DC layout as shown in the Fig. 4.2 consists of circular arc waveguide segments to form symmetric S-bends that converge to parallel, symmetric waveguides, closely separated by coupling distance, $d$, over a coupling length, $L_c$.

![Figure 4.2: Schematic layout of a DC composed of two waveguides with circular arc segments to bring the waveguides together with a coupling distance, $d$, and coupling length, $L_c$.](image_url)
A standard transfer-matrix method is used to model the DCs using a $2 \times 2$ system matrix, $M_{\text{DC}}$, to relate the output electric field ($E_3$ and $E_4$ at ports 3 and 4, respectively) to the input fields ($E_1$ and $E_2$ at ports 1 and 2, respectively):

$$
\begin{pmatrix}
E_3 \\
E_4
\end{pmatrix} = M_{\text{DC}}
\begin{pmatrix}
E_1 \\
E_2
\end{pmatrix}
$$

(4.1)

In addition, the power coupling ratio, $r_j$, defined for the output ports, $j = 3$ or 4, were extracted from the square of the fields:

$$r_j(\lambda) = \frac{P_j}{P_3 + P_4} = \frac{E_j^2}{E_3^2 + E_4^2}, \quad j = 3, 4. \tag{4.2}$$

The power coupling ratios for laser formed DCs were found to be well described by coupled mode theory (CMT) [24], according to the sinusoidal response:

$$r_j(\lambda) = A \sin^2[\theta_{\text{DC}}(L_c, \lambda)], \quad j = 3, 4. \tag{4.3}$$

Here, $A$ is the maximum power transfer ratio that is expected to equal one for the present case of symmetric waveguides, and less than one as the coupling waveguides become asymmetric. The coupling phase, $\theta_{\text{DC}}(L_c, \lambda)$, is defined as:

$$\theta_{\text{DC}}(L_c, \lambda) = \kappa(\lambda)L_c + \phi(\lambda), \tag{4.4}$$

where $\kappa(\lambda)$, is the coupling strength between the waveguides that depends on the waveguide separation distance, $d$, and $\phi(\lambda)$ is an additional phase shift to account for coupling that occurs between the waveguides within the S-bends [87].

Although $L_c$ can be easily varied in the circuit design to provide an optimum DC splitting ratio, $r_j$, both the magnitude and the wavelength dependence in $\kappa(\lambda)$ and $\phi(\lambda)$ are highly varied with the waveguide layout and laser exposure conditions [43, 87] that
can dramatically limit the spectral bandwidth of the device. Also, the additional losses through the DC were symmetric in both waveguide arms and small (< 0.1 dB) relative to typical waveguide losses to yield the following transfer matrix for the lossless DC:

\[
M_{DC} = \begin{pmatrix}
\cos(\theta_{DC}) & i\sin(\theta_{DC}) \\
 i\sin(\theta_{DC}) & \cos(\theta_{DC})
\end{pmatrix}
\] (4.5)

To characterize the directional coupler response under the current laser writing conditions, a series of symmetric DCs were written with the minimum waveguide separation fixed at \(d = 8 \, \mu\text{m}\) and coupling lengths varied from \(L_c = 0\) to 2 mm in 0.2-mm steps. Fig. 4.3 shows the measured coupling ratios calculated from Eq. 4.3 for 1310 nm and fitted according to Eq. 4.5 to yield \(\kappa(\lambda)\), \(\phi(\lambda)\), and \(A(\lambda)\) values of 1.398 mm\(^{-1}\), 1.021, and 0.994, respectively, for port 3. This corresponds to a beat length of 2.247 mm that permitted selection of any DC coupling ratio \((r = 0\) to 1) down to a low -25 dB crosstalk for coupling lengths under 1.124 mm. Interpolation of the present data offered coupling

![Figure 4.3: The measured coupling ratio, \(r_3\) and \(r_4\), at 1310 nm for DCs of various coupling lengths and the representation of Eq. 4.3 (solid lines) with DC matrix parameters: \(\kappa = 1.398\ \text{mm}^{-1}\), \(\phi = 1.021\), and \(A = 0.944\) and a coefficient of determination, \(R^2 = 0.99956\).](image)
4.3 Mach-Zehnder Interferometer

Now that the DC groundwork has been laid, a MZI can be designed and fabricated from two DCs connected with waveguide arms of different lengths. Their spectral response was modelled by separating the device into a phase response component, $M_{\Delta \theta_p}$, and a propagation loss response component, $M_\alpha$, as shown below:

$$M_{\Delta \theta_p} = \begin{pmatrix} \exp\left(\frac{i \Delta \theta_p}{2}\right) & 0 \\ 0 & \exp\left(-\frac{i \Delta \theta_p}{2}\right) \end{pmatrix}, \text{ where } \theta_p = \frac{2 \pi n_{\text{eff}}(\lambda) \Delta L}{\lambda}, \text{ and }$$

Figure 4.4: Spectral response of a single DC with coupling length, $L_c = 0.955$ mm, yielding a nearly flat $3.0 \pm 0.5$ dB coupling ratio over a 30-nm bandwidth between 1296 and 1326 nm.

lengths of $L_c = 0.955$, 0, and 0.230 mm to meet the respective 50.0%, 72.8%, and 92.6% coupling ratios required in the present FTI design for operation around 1310 nm.

The DC spectral response, $r(\lambda)$, for a 3-dB coupler design at 1310 nm was assessed as shown in Fig. 4.4, yielding a relatively flat wavelength dependence of $3.0 \pm 0.5$ dB ($50 \pm 5\%$) between 1296 to 1326 nm that predicts a 30-nm spectral window for favourable FTI response.
\[ M_\alpha = \begin{pmatrix} 10^{-\frac{1}{10} \alpha_s(\lambda)L_{s1} + \alpha_c(R,\lambda)L_{c1}} & 0 \\ 0 & 10^{-\frac{1}{10} \alpha_s(\lambda)L_{s2} + \alpha_c(R,\lambda)L_{c2}} \end{pmatrix} \] (4.7)

The path difference, \( \Delta L \), between the waveguide arms combined with the effective index, \( n_{\text{eff}}(\lambda) \), of the device introduces a relative phase delay, \( \Delta \theta_p \), between the waveguide arms, which results in a spectral fringe pattern as shown in Fig. 4.5. In this example, both output arms had been characterized for the input coupled into both input arms and overlaid on the same graph to demonstrate the symmetry and process variability for two identically designed MZIs for the 1560 nm of the broadband input source. The shape of the spectral output is mainly a function of the input source used to characterize the MZI, but also of the wavelength-dependent propagation losses that depend on the straight and curved decay constants \( \alpha_s(\lambda) \) and \( \alpha_c(\lambda) \) and the lengths of these sections, \( L_s \) and \( L_c \), respectively. The MZI arms differed greatly in the proportion of straight

![Image](image-url)

**Figure 4.5:** Spectral response of two MZIs under various input and output conditions. The experimental response for both output arms with the input coupled to each input arm to demonstrate the symmetry and process variability for two identical MZIs, optimized for the 1560 nm peak of the broadband input source. The shape of the spectral output is a result of the spectral shape of the broadband input used to characterize the MZIs, but also of the wavelength-dependent propagation losses.
and curved sections, which results in strongly asymmetric losses between the arms. This dramatically alters the power ratio in the exit port waveguides reducing the channel contrast and required compensation in the DC design to unbalance the power splitting ratios.

The phase delay between the MZI arms was modelled by extracting a linear estimate of \( n_{\text{eff}}(\lambda) = 1.4736 - 1.7891 \times 10^{-5}\lambda \) from the fringe spacing observed in a MZI over the 1250 to 1350 nm range, with the chromatic dispersion of the device in the region of its flat passbands approximated to follow that of fused silica. Given the small refractive index modification induced by laser writing, the waveguide contribution to the chromatic dispersion was expected to be much less than that of the material dispersion.

### 4.4 Flat-Top Interleaver

An FTI further builds upon the simpler DC and MZI components discussed in the previous sections as an example of an integration of a more complex, integrated optical circuit in bulk glass with the goal of demonstrating process accuracy and fabrication consistency. Loss, phase delay, coupling strength and wavelength dependence were characterized for these sub-components to facilitate an accurate modelling design that could balance trade-offs between loss, component size, and process variability and thereby deliver an optimized FTI design across a broad spectral window. Despite moderate variability in the laser process and component responses, the modelling permitted an FTI device to be fabricated by direct laser writing. Hence, the feasibility for laser writing to form highly functional integrated multi-component photonic systems is demonstrated.

An integrated four-port FTI circuit based on two cascaded MZIs was selected that combines several four-port optical devices including the three DCs as shown in Fig. 4.6.
Figure 4.6: Schematic design for the four-port FTI composed of two cascaded MZIs with input and output ports labelled as 1 and 2, and 3 and 4, respectively, together with a magnified (inset) view of a single DC with coupling distance, $d = 8\, \mu m$. The optimized FTI design requires coupling lengths of $L_c = 0.955, 0.000, \text{ and } 0.236\, \text{mm}$ (left to right for the 3 DCs) and the indicated path length differences, $\Delta L$.

Following the standard transfer-matrix method, the overall system transfer matrix for the four-port FTI was segmented as follows:

$$M_{\text{FTI}} = M_{\text{DC}_3}(M_{\Delta \theta_{p2}}M_{\alpha_2})M_{\text{MZI}_2}M_{\text{DC}_2}(M_{\Delta \theta_{p1}}M_{\alpha_1})M_{\text{MZI}_1}M_{\text{DC}_1},$$

(4.8)

where the DC coupling responses are represented by $M_{\text{DC}_1}$, $M_{\text{DC}_2}$ and $M_{\text{DC}_3}$, the asymmetric propagation losses by $M_{\alpha_1}$ and $M_{\alpha_2}$, and the phase delays by $M_{\Delta \theta_{p1}}$ and $M_{\Delta \theta_{p2}}$, which are imposed by the two waveguide arms of each MZI section. The FTI power coupling ratio, $r_j$, of the output ports, $j = 3$ or 4, were measured according to Eq. 4.3.

The FTI was designed and written on $76.2\, \text{mm} \times 50.8\, \text{mm} \times 1\, \text{mm}$ fused silica substrates using the same writing conditions as for the waveguides described in Section 4.1. The transfer matrix response functions described above were constructed through successive stages of laser fabrication and characterization of individual waveguides and four-port DC and MZI devices. A range of laser exposure conditions was explored as described in Section 4.1 to minimize waveguide loss while also seeking a small bend radius for compactness of the back-to-back MZI design to fit over 3-inch wide glass substrates. In
this case, waveguides were limited to 35 mm bend radius, limiting the maximum path differences that could be generated over the 3-inch wide substrate to $\Delta L_1 = 192.9 \, \mu m$ and $\Delta L_2 = 385.8 \, \mu m$ for the cascaded MZI to yield a minimum FTI channel bandwidth of 3 nm at 1310 nm. Larger channel separation can be arbitrarily designed with smaller path differences, up to the symmetric $\Delta L = 0$ case.

With these constraints, the smallest channel spacing of 3 nm was targeted together with DC coupling ratios of 50.0%, 72.8%, and 92.6% that were previously optimized in planar lightwave circuits [91] to generate wide flat-top passbands with low crosstalk. A convergence of the measured and simulated spectral response was finally sought to provide a balanced interleaver response over the broadest spectral window.

The FTI design was focused in the 1250 to 1325 nm spectral range of Fig. 4.1, where propagation loss of all the straight and curved waveguides was lowest ($< 1.00 \, \text{dB/cm}$). Design wavelengths of 1310 nm and 1391 nm were identified for the 35 mm and 75 mm radius waveguides, respectively, that would provide nearly identical propagation losses of 0.71 dB/cm and 0.94 dB/cm, respectively, for balancing losses in the both arms of each MZI. While the lower loss and flatter wavelength response of the larger 75 mm radius waveguides would provide a broader interleaver spectrum, the lower 35 mm radius waveguides were selected for both the DC and MZI curved sections to provide a five-fold denser channel spacing and more compact design. The propagation loss data in Fig. 4.1 provided the $\alpha_s(R = \infty, \lambda)$ and $\alpha_c(R = 35 \, \text{mm}, \lambda)$ matrix elements required in Eq. 4.7.

To counter modal offset losses [92] at the inflection points where waveguide curvature is flipped or meets straight waveguides, the circuit design in Fig. 4.6 was modified to offset waveguides by 0.8 or 0.4 $\mu m$, respectively, and reduced loss by an average of 0.16 dB per inflection point. Other means to reduce such transition loss by writing waveguides with varying radius (i.e. sinusoidal) or width were not explored. Additional transition losses were expected to arise from using two different scan speeds that yield slightly different
mode sizes and refractive index profiles, but these losses were more than offset by the net improvement (\(\sim 0.7 \text{ dB}\)) in transmission in curved sections written at lower speed.

The FTI design for the optimized waveguide device parameters were calculated from the FTI matrix response in Eq. 4.8 and its spectral response was characterized according to the power coupling ratio presented in Eq. 4.3 and plotted in Fig. 4.7 (solid lines) against the spectral response recorded from the associated laser-fabricated FTI prototype (dashed lines). An accurate spectral alignment was found between the design and prototype channels for both output ports (3 and 4), coinciding within \(\pm 0.01 \text{ nm} \ (\pm 0.3\% \text{ of FSR})\) for the 1310 nm channel and increasing to \(\pm 0.1 \text{ nm} \ (\pm 3\%)\) at 1269 and 1341 nm. A moderately low crosstalk of \(> 15 \text{ dB}\) was maintained between the output ports across a 30-nm operating band from 1287 and 1317 nm, attesting to the high precision and reproducibility of laser fabrication without the need for phase trimming of the MZI arms. The transmission isolation fell \(\sim 10 \text{ dB}\) short of the 25 dB design values expected near 1310 nm, potentially arising from small variations in the laser exposure control that lead to varied waveguide properties \((n_{\text{eff}}(\lambda) \text{ and } \alpha(\lambda))\), detuned DCs, or phase errors in the MZI arms. Moving away from the design wavelength, the coupling ratios for both measured and predicted responses became increasingly unbalanced due to the limited 30-nm bandwidth found in Fig. 4.4 for the present 3-dB coupler design. The contrast degrades further to \(< 10 \text{ dB}\) for longer wavelengths, \(\lambda > 1340 \text{ nm}\), due to the strongly increased bend loss anticipated in the longer MZI waveguide arms by Fig. 4.1 \((R = 35 \text{ mm})\) that unbalance the power ratios at the DCs. Nevertheless, a -10 dB crosstalk was maintained on all FTI output ports over a large 70 nm range from 1270 to 1340 nm.

The flat-top response of the FTI in Fig. 4.7 was characterized by a 0.5-dB passband width of 1.85 nm for the 3-nm channel spacing at 1308 nm. An average 0.5-dB passband of 1.75 nm was found for the five channels in the 1290 to 1317 nm band, representing a 46% wider passband that meets closely with the 50% widening expected over a single
MZI interleaver design. Outside of this spectral window, the 0.5-dB passband narrowed to values as low as 1.2 nm ($\lambda > 1338$ nm) and became double peaked ($\lambda < 1269$ nm) for the port 4 channels, owing to imbalance in the MZI arm loss, MZI phases, and DC splitting ratio.

The propagation loss of the FTI shown in Fig. 4.1 was inferred from the insertion loss spectrum that gives a value of 9.3-dB loss at the 1310 nm design wavelength. The minimum propagation loss of $1.5 \pm 0.1$ dB/cm found in the 1250 to 1310 nm aligns well with the 1287 to 1317 nm operating range of the optimized interleaver response in Fig. 4.7. The interleaver loss increased strongly to $> 3.6$ dB/cm with longer wavelength, $\lambda > 1430$ nm, that followed the trend of losses for the $R = 35$ mm curved waveguide in Fig. 4.1.

**Figure 4.7:** The measured (Exp) and simulated (Model) transmission spectra for the FTI was converted into the power coupling ratio described in Eq. 4.3 for comparison showing good agreement between the design and the device spectra. The measured crosstalk of less than -15 dB was observed over a 30-nm spectral band of 1287 to 1317 nm, for the channel spacing of 3 nm. For shorter wavelengths, double-peaked responses was observed as the coupling response of individual FTI components drifted away from the 1310-nm design wavelength.
Immersion of the FTI into ice water yielded a small 0.5 nm spectral shift from room temperature, illustrating a very small temperature dependence of \(\sim 0.03 \text{ nm/}^\circ\text{C}\) or 1% FSR/\(\circ\text{C}\) around 1310 nm.

Several directions are available for further improving the spectral response of the femtosecond laser written interleaver. A reduction of total insertion loss particularly towards longer wavelengths into the C- and L- telecom bands requires development of stronger guiding waveguides with bend loss falling well below the 5.0 dB/cm values seen in Fig. 4.1 for \(\lambda > 1430 \text{ nm}\). Femtosecond laser writing with high NA oil immersion lenses is one promising approach in this direction that offers two-fold smaller mode sizes (i.e. 7.2 \(\mu\text{m}\) mode field diameter) and two-fold higher refractive index contrast [90] such that higher curvature waveguides could be exploited for creating more compact MZI and FTI devices with higher channel isolation and denser channel spacing. The FTI bandwidth was restricted by the narrow 30-nm bandwidth in the present symmetric DC design (Fig. 4.4), while a 10-fold bandwidth improvement has been found previously with asymmetric DCs laser-written in borosilicate glass [43]. The FTI was analyzed for a single linear polarization to avoid birefringence (\(\Delta n \sim 5 \times 10^{-5}\)) [22] effects in the laser written waveguides. Harnessing heat-accumulation effects such as observed in waveguides formed in borosilicate glass [23] can offer much lower birefringence to aid in developing a polarization insensitive interleaver. The flat-topped FTI response in Fig. 4.7 demonstrates the precision of matrix modelling as a design tool that can now be reliability applied to femtosecond laser writing of waveguides to develop more functional optical circuits. Design approaches were applied here to account for various loss, phase and power splitting imbalances and enable femtosecond laser writing in a single step process without complex trimming procedures. As the capabilities of femtosecond laser fabrication improve, this design approach will facilitate more practical device applications into areas such as spectral shaping and polarization control or phase-array waveguide gratings to exploit the three-dimensional (3D) advantage of the laser writing process.
4.5 Summary

In summary, the design optimization and fabrication of an integrated five-component flat-top interleaver was demonstrated by using femtosecond laser writing of optical waveguides, DCs, and MZIs in bulk glass. The laser processes and design were sufficiently robust to produce 46% widened 0.5-dB flat-top response with channel crosstalk below -15 dB over a 30 nm bandwidth. Overall, the transfer matrix model successfully captured the phase and loss responses through multiple photonic components for predicting the spectral response of the FTI, with spectral alignment within ±0.01 nm or 0.3% of the 3 nm channel spacing. The results demonstrate the accuracy and reproducibility of the femtosecond laser writing of more functional 3D optical circuits inside bulk transparent glass, which is important for the complex, multi-stage, multi-component photonic devices in the following chapters.
Chapter 5

Thermal Poling of Waveguides in Fused Silica

Thermal poling is a method for inducing nonlinear responses within fused silica through the application of high temperatures and voltages in a process described in detail in Section 3.3. However, the effectiveness of this process becomes limited when combined with femtosecond laser processing due to erasure and blocking processes. When fused silica samples are poled first, the laser writing process erases the nonlinearity, while when the waveguides are written first, a blocking effect occurs as the poling process becomes disrupted by the nanolayers within the laser modified region [32,70,93].

The physical interaction between thermal poling and femtosecond laser writing was investigated systematically by the methods of Section 3.4 to determine the effect of femtosecond laser writing of waveguides on the thermal poling of fused silica and the effect of repoling the glass after writing the waveguides. Three processes were studied: (1) the fused silica glass plate was thermally poled first before the waveguides were written, which we call pre-poling; (2) the waveguides were written first and then the plate was thermally poled, which we call post-poling; and (3) double poling refers to the process where the plate was thermally poled both before and after the laser writing of waveguides. Second-harmonic (SH) microscopy described in Section 3.4 was used
to characterize the induced second-order nonlinearity by thermal poling and generate near-surface two-dimensional (2D) cross-sectional images from cleaved silica samples. A relative strength parameter was used to quantify the induced nonlinearity within the waveguide region, which was measured to be 0.16, 0.74, and 1.06 for the pre-poled, post-poled, and double poled samples, respectively. Double poling was found to overcome the prior difficulties with combining these two processes and provides a future avenue for creating active nonlinear devices using femtosecond laser writing in fused silica.

5.1 Sample Preparation

The optical waveguides were written in 50.8 mm × 25.4 mm × 1 mm fused silica substrates with the IMRA femtosecond laser system described in Section 3.1 using similar writing conditions as the linear waveguides described in Section 4.1. A slightly lower input power of 85 mW of 522 nm pulses were used for these experiments due to shifts in the laser’s operating state, but similar low-loss waveguides (∼0.5 dB/cm at 1550 nm) were achieved. To optimally position the waveguide within the ∼12 µm thick ion depletion zone created during thermal poling, waveguides were written at vertical offset intervals of 2 µm from the surface. A minimum depth of 11 µm was observed, limited by the onset of surface ablation.

Fused silica substrates were thermally poled via pre-poling, post-poling, and double poling in order to induce a second-order nonlinearity (SON) within the glass using the custom built thermal poling station described in Chapter 3. During each poling stage, samples were heated to 300°C and biased at 3.5 kV for 1 hour.

5.2 Second Harmonic Characterization

A custom SH characterization system was also designed and built for the IMRA laser system to characterize the effects of thermal poling on the glass substrates as described
in Section 3.3. The system enabled 2D visualization of the induced nonlinearity within the substrate cross-sections through observation of a SH signal, with a spatial resolution of $\sim 1 \, \mu m$. This signal was analyzed around the vicinity of the femtosecond laser written waveguides according to a process described in greater detail in Section 3.3.

A sample set of SH images collected for a pre-poled sample is shown in Fig. 5.1. Surface and waveguide features were identified for each image near the top anode surfaces and used to align the various collected images against each other. A white light micro-

![Figure 5.1: Waveguide cross-section under various illumination conditions. Images were aligned with respect to the anode-exposed glass surface (marked by arrows) and waveguide features. Red dashed circles mark the $1/e^2$ diameter of the waveguide mode at a depth of 12 $\mu m$ for (a-d). (a) Linear transmission image recorded with a white light microscope. (b) Linear transmission image of 522 nm laser ($<2 \, mW$) recorded with the SH characterization setup. (c) SH transmission image excited by 1044 nm laser source (15 mW) and recorded with the same SH characterization set up through a 520-nm bandpass filter. A uniform SH generation zone of $\sim 12 \, \mu m$ depth is seen to be diminished in the waveguide zone. (d) Same as (c) with 520-nm wavelength, 28-nm wide bandpass filter replaced with 526-nm, 17-nm wide notch filter to confirm SH generation in the case of (c). Inset (e) shows the mode profile of a laser written waveguide having a MFD of 11.3 $\mu m \times 11.6 \, \mu m$.]

5.3. Poling Effects

Scope image of a typical waveguide cross-section is shown in Fig. 5.1 (a) to reveal a 2 µm × 13 µm positive index zone (white zone) centered at 12 µm below the surface (arrows). The waveguide cross-section was also recorded by directly measuring a transmitted, low power (< 2 mW) 522-nm laser beam with the SH characterization arrangement, yielding the image in Fig. 5.1 (b). The dark zones align with scattering of light from the laser modification track. SH images at 522 nm wavelength were recorded as seen in Fig. 5.1 (c) with 1044 nm input light applied up to the observed damage threshold of the epoxy (~15 mW), and with laser field polarized parallel to the internal DC field (vertical in images). Strong SH signals were observed up to a depth of 12 µm, except in the vicinity of the waveguide where an erasure effect was observed.

Replacing the 520-nm wavelength, 28-nm wide bandpass filter with the 526-nm wavelength, 17-nm wide notch filter for the same recording condition was found to reduce the SH signal to the near-noise level of detection as seen in Fig. 5.1 (d), confirming the SH generation in the anticipated ion-depletion zone. A weak (red) signal zone (left and right arrows) corresponding to laser-induced damage at the epoxy interface was observed near the edges where excessive laser exposure resulted from multiple scans (~30) and increased dwell times due to deceleration effects of the translation stages.

5.3 Poling Effects

To explore the interaction between laser-formed waveguides and thermal poling, three different conditions of (1) pre-poling, (2) post-poling, and (3) double poling were tested with respect to the waveguide formation step. For the double poled condition, samples were poled twice, once before and once following laser writing. A fourth unpoled condition also tested laser formed waveguides without a thermal poling step.

Microscope images of waveguide end-views are shown in Fig. 5.2 (a-d) for each of the four poling conditions, and followed with images of SH generation in Fig. 5.2 (e-h). An overlay of the SH and optical microscope images in Fig. 5.2 (i-l) verifies the position
of the SH signal with respect to the waveguides. In all combinations of pre- and post-
thermal poling, strong bands of SH signal (green) were observed to a depth of 12 µm
below the glass surface (Fig. 5.2, e-g), near the minimum depth of the laser fabricated
waveguides. Longer poling durations increase the nonlinearity deeper into the glass, but
has been observed to reduce the strength of this nonlinearity [94].

The depth profile of the SH signal was sensitive to the alignment of the SH microscopy
system, and was optimized to produce the sharpest resolution centered at the waveguide
position. In general, two horizontal bands were observed for poled samples, with a
variation in the SH signal observed in the vertical direction, which is attributed to sample
packaging and alignment. This spatial variation in the vertical direction is hypothesized
to result from the probe beam passing through numerous interfaces with optical paths
differing along this dimension as a result of sample tilt and focal depth. Poling zones were
typically uniform across the horizontal axis, which is parallel to the surface interfaces,
except in the vicinity of the waveguides and the effect of femtosecond laser writing on
thermal poling is characterized along this uniform poling axis. In the current examples,
wide poling zones were generated by the single poling cases and thin sharp bands were
noted for the case of double poling. SH signals were not observed in the absence of
thermal poling for the unpoled samples (Fig. 5.2, h), or at any of the cathode-facing
surfaces.

The optical images in Fig. 5.2, (a-d) show evidence of stress forming laterally from the
waveguides, which has been previously characterized with crossed polarized imaging in
prior work under similar writing conditions [95]. These stress zone reach several tens of
microns away from the waveguide (Fig. 2 in [95]) in contrast with the blocking zone under
poling that varies from ∼20 µm in pre-poling (Fig. 5.2, i) to ∼5 µm in double poling
(Fig. 5.2, k). Hence, the blocking effect in poling appears to be more directly affected
by the laser-modification structure immediately in the vicinity of the waveguide zone,
rather than the longer reach stress field. The poling zone is uniform along the surface,
Figure 5.2: SH images of various poling conditions. Optical microscope images (a-d) of waveguide positions (white vertical line) under backlighting for cases of pre-poled (a), post-poled (b), double poled (c), and unpoled (d) samples followed with the images of the SH generated signals observed over the same waveguide area for each of the poling and unpoled cases (e-h). A superposition of the top and middle row images (i-l) show the expected waveguide mode position (red dashed circle) and varying degrees of waveguide erasure and blocking effects for pre-poled (i), post-poled (j), and double poled (k) cases. SH signals were not observed from the unpoled samples (h, l) or the glass surface contacted with the cathode (not shown).
except in the proximity of the waveguide. Here, the SH generation is significantly altered, shrinking dramatically for the pre-poled case (Fig. 5.2, e), moderately in the post-poled case (Fig. 5.2, f) and only marginally in the double-poled case (Fig. 5.2, g). The spatial distribution of this poling erasure or blocking effect will significantly affect the nonlinear response of the waveguide according to the waveguide mode diameter of 11.4 µm ($1/e^2$).

To quantify this effect, the SH-generated signal, $P_{SH}(x,y)$, was digitally integrated with a Gaussian-weighted function, $G(x,y)$, matched to this mode diameter to provide an effective nonlinear waveguide interaction strength, $\sigma(x_0,y_0)$, defined as:

$$\sigma(x_0,y_0) = \int G(x-x_0,y-y_0)P_{SH}(x,y)dxdy$$

(5.1)

This calculation was centered at $y_0 = 12\mu m$ depth, corresponding to the position of the waveguide mode, and repeated for positions scanned transversely along this facet view to yield $\sigma(x_0,y_0 = 12\mu m)$ as shown in Fig. 5.3 for the case of post-poling. An overall parabolic dependence (dashed line) on the position arises from increased measurement dwell time as the stages decelerate at the turning points ($x_0 = \pm 112.5$). Upon correcting for this position-dependent acceleration, $\sigma(x_0,y_0)$ for each poling condition was replotted in Fig. 5.4 in an expanded view around the 11.4 µm wide waveguide zone (yellow bar).

The results for each poling case were normalized to a baseline value of 1 taken outside the waveguide zone to allow a relative comparison of nonlinear strength at the waveguide zone. An absolute measurement for conversion efficiency could not be meaningfully calculated due to measurement inaccuracies and uncertainties throughout the current apparatus, e.g. varying coupling efficiency into a large multi-mode fiber, and power measurements from photon counting.

For the pre-poling (blue) and post-poling (green) conditions in Fig. 5.4, $\sigma(x_0,y_0)$ was found to decrease significantly at the waveguide position by 81% and 26%, respectively, while the doubling poling case (red) indicated a possible increase of 6% from the baseline. In the pre-poled case (Fig. 5.2, e), a very large zone (53 µm wide by 12 µm height) of weak
SH generation around the waveguide manifested in a very strong depletion of $\sigma(x_0, y_0)$ in Fig. 5.4 (blue line), extending over a 50 µm width. This significant erasure of the poling effect by laser writing may arise from a high ion mobility enabled during the laser heating cycle during a laser dwell time of 6 ms. Redistributed ions are then expected to sharply weaken the frozen-in field in this heat-affected zone.

The SH generation signal was also strongly weakened in the post-poled samples (Fig. 5.2, f) but only in a narrow $\sim$5 µm zone in the immediate proximity of the laser modification track. In this case, the expected presence of porous nanolayers, previously observed in laser written waveguide cross-sections [70], may have acted as a barrier to ion migration during the thermal poling process. The overall effect is a more moderate depletion of $\sigma(x_0, y_0)$ in Fig. 5.4 (green line) to 74% potential nonlinearity given the larger 11.4 µm mode size over the 5 µm depletion width. This narrow blocking effect is expected from the highly localized positioning of the nanogratings [96] in the strong laser interaction zone as opposed to the thermal erasing effect anticipated for the pre-poling case of Fig. 5.4 (blue line). The combination of pre- and post-poling led to the imaging of two thin poling zones ($\sim$2.5 µm in Fig. 5.2, g) in contrast with the $\sim$8 µm wide zone.

![Figure 5.3](image-url)

**Figure 5.3:** Effective nonlinear waveguide interaction strength, $\sigma(x_0, y_0)$, calculated along the sample surface transversely offset from the waveguide position at $y_0 = 12$ µm depth in the post-poled case. An underlying parabolic dependence (grey dashed line) was observed from increased measurement dwell times during the motion stage deceleration. The central dip diameter of 5 µm was observed as a reduction in the poling zone in the vicinity of the waveguide.
Figure 5.4: Normalized comparison across poling conditions after correcting for parabolic dependence in an expanded view around the 11.4 µm waveguide mode (yellow bar). Strong erasing (81% decrease) and blocking (26%) effects in the respective pre-poled (blue) and post-poled (green) cases are avoided in the double poled samples (red).

observed in the pre-poling sample (Fig. 5.2, e) or the post-poling (Fig. 5.2, f) cases. Owing to the alignment sensitivity of the SH collection system, it is unclear if thinner poling zones will reduce or enhance the overall nonlinear response of the waveguide or was an artifact of the alignment system. The strong benefit of the double poling is seen in both the SH generation image of Fig. 5.2(g) and in \(\sigma(x_0, y_0)\) in Fig. 5.4 (red line), where only a very narrow 3 µm wide non-generation zone was observed, representing only one-quarter of the waveguide mode size. The ion blocking effect noted in the post-poled samples is less pronounced here, diminished by the initial pre-poling step. Fig. 5.2(g) also reveals a \(\sim 25\%\) enhancement in SH signal strength above the poling baseline in small zones (1.5 µm size) adjacent to the 3 µm wide waveguide, suggesting a redistribution of the ions around the waveguide zone. Hence, the combination of pre-poling and post-poling of the fused silica substrate (Fig. 5.4, red line) is promising in providing the full nonlin-
ear interaction strength of the induced nonlinearity to the waveguide mode over a MFD
diameter of 11.4 µm.

5.4 Summary

Fused silica glass was thermally poled and visualized using SH microscopy. Through
systematic investigation of various poling approaches, a double poling method was found
to effectively induce a SON in laser written waveguides in fused silica. The combination
of poling both before and after laser writing led to the least disruption of the induced
nonlinearity. The effective nonlinear waveguide interaction strength was quantified and
observed to match with the SH generation rates in the poling zones outside of the waveg-
uide disturbance zone, exhibiting an improvement over traditional single stage poling
methods. These results open up the possibility of using thermal poling to induce a
permanent nonlinearity into femtosecond-laser written devices, which could be used to
create active and nonlinear devices in fused silica. An example of such a nonlinear device
is demonstrated in the following chapter in the form of a quasi-phase-matched (QPM)
second-harmonic generation (SHG) waveguide.
Chapter 6

SHG in Femtosecond Laser Written Waveguides

In this chapter, maskless quasi-phase-matched (QPM) second-harmonic generation (SHG) with perfect phase-matching was demonstrated in femtosecond laser written waveguides in fused silica for the first time. A single femtosecond laser system was capable of performing nearly all the fabrication steps in a simplified process. A pre-existing challenge presented by the interaction between thermal poling and femtosecond laser writing had previously prevented had greatly restricted the ability to effectively pole femtosecond laser waveguides. The poling technique developed in Chapter 5 overcame these challenges to induce a sufficiently large second-order nonlinearity inside the laser-written waveguide zone.

The remaining key challenge was in phase-matching the nonlinear interaction over a long waveguide length, requiring additional modification of the thermal poling, for example, by QPM as found in poled fibers. In this process, the entire length of a uniform thermally poled waveguide would usually be subjected to a periodic erasure of the induced nonlinearity, often using UV mask erasure [35], or continuous point erasure [36]. In 2009, Li et al. used e-beam deposition, and a complex photolithographic step to develop QPM SHG [37]. Despite applying temperature tuning, the device could not be driven to
perfect phase matching, leaving a residual phase mismatch of $\Delta kL = 3\pi$ and weak SHG conversion efficiency. In this chapter, a new laser-based erasure technique was developed and presented in order to achieve flexible, and arbitrary QPM by the periodic erasure of induced nonlinearity within the poled samples.

On optimization of the QPM, the demonstration of SHG in a femtosecond laser written waveguide in fused silica resulted in a SHG conversion efficiency of $1.3 \pm 0.1 \times 10^{-11}/\text{W-cm}^{-2}$ for the fundamental wavelength of 1552.8 nm with a phase-matching bandwidth of 4.4 nm for a 10.0-mm-long waveguide. For a shorter sample, an effective second order nonlinearity of $\chi^{(2)} = 0.020 \pm 0.002 \text{ pm/V}$ was measured. Chirped QPM structures for wider SHG bandwidths were also demonstrated. Such periodically poled waveguides are promising for introducing nonlinear optical components within the three-dimensional passive optical circuits that can be flexibly formed in fused silica by femtosecond laser writing.

### 6.1 Sample Preparation

Femtosecond laser waveguides were written into 50.8 mm $\times$ 25.4 mm $\times$ 1 mm fused silica substrates and poled using the femtosecond laser writing system and thermal poling system described in Chapter 3. The pulse energies were optimized to reduce losses at the second-harmonic (SH) wavelength, 775 nm, while maintaining low losses (<1 dB/cm) at the fundamental wavelength, 1550 nm. Using the procedure in Section 3.1, propagation losses as a function of power were shown in Fig. 6.1 where sets of waveguides were written with various scan speeds and pump powers. The typical writing parameters used for 1550 nm waveguides resulted in propagation losses of $>10 \text{ dB/cm}$ at 775 nm. Transmission in the fundamental wavelength was prioritized over the SH wavelength due to the increased efficiency dependence on the fundamental, as predicted in Section 2.4. As a result, 100 mW power exposure was selected as a balance to yield propagation losses of $0.88 \pm 0.01 \text{ dB/cm}$ and $4.27 \pm 0.02 \text{ dB/cm}$ for fundamental and SH wavelengths,
Chapter 6. SHG in Femtosecond Laser Written Waveguides

Figure 6.1: Waveguide propagation loss as a function of writing laser power for fundamental and SH wavelengths. Losses at 775 nm decreased linearly with lower writing powers, while losses at 1550 nm increased significantly below 95 mW.

respectively, while written at a depth of 12 µm by using pulse energies of 100 nJ and a scan speed of 100 µm/s. These results were nearly independent (<1%) of input polarization for these laser written waveguides which displayed very low birefringence for 1550 nm. While lower scan speeds were found to improve losses at both wavelengths, 100 µm/s was selected as the practical lower limit for these experiments. This improvement in waveguide transmission was likely a result of reduced optical scattering due to more uniform waveguides observed with lower scan speeds. Upon femtosecond laser erasure at a later stage, propagation losses increased to 1.3 dB/cm and 6.7 dB/cm for 1550 and 775 nm, respectively, as the additional exposure caused additional modification of the waveguides.

Thermal poling was applied using the 3 kV poling voltage, 300°C heating for 1 hour as described in Section 3.3 along with the double poling procedure developed in Chap. 5 to induce a effective second-order nonlinearity (SON) peaking at 12 µm below the anode surface.
6.2 Femtosecond Laser Erasure

A femtosecond laser erasure process was developed for erasing locally the induced nonlinearity to create a QPM structure using the same above-mentioned laser system, at the same wavelength, repetition rate and pulse duration. The erasure process was optimized for erasure resolution, nonlinearity contrast, and speed. A 0.50 numerical aperture (NA) lens was used to focus 80 nJ pulses at a depth of 6 µm while scanning the substrates at a faster speed of 10 mm/s to selectively erase the induced nonlinearity. The post-erasure cross-sections of the substrates were imaged with the SH microscopy system described in Section 3.4 with the resulting images shown in Fig. 6.2. Single tracks from Fig. 6.2(a) formed at a 12 µm depth created a strongly contrasting (~60:1), 4.0 µm wide region within the otherwise uniform band of nonlinearity at the depth of approximately 12 µm. Multiple tracks of the same type, spaced by 4.4 µm and formed into bands of 6 tracks were stitched together to create a larger 26.2 µm erasure region, representing a 48% duty cycle over the 54.2 µm QPM periods shown in the image. These tracks were not optically visible when viewed under the microscope.
Chapter 6. SHG in Femtosecond Laser Written Waveguides

Figure 6.3: Illustration of QPM waveguide after the erasure of induced nonlinearity (green) overlaid on top of the laser-written waveguide (white). Mode profiles for 1550-nm and 775-nm are shown on either side.

The QPM structure was written by scanning stitched erasure tracks perpendicularly to the femtosecond waveguide (white) as shown in Fig. 6.3, leaving behind a periodic nonlinearity induced by thermal poling (green). The waveguide mode profiles are also shown in Fig. 6.3, with measured 1/e²-intensity beam widths of 12.8 µm × 12.4 µm and 6.5 µm × 9.7 µm for 1550 nm and 775 nm, respectively.

6.3 Phase-Matching Process

The QPM waveguides were characterized using the Luminos characterization system described in Section 3.2 and the specific configuration shown in Fig. 6.4. A tunable (1529-1546 nm), 1 MHz, 500-ps fiber laser (Genia Photonics MOPA) was amplified by

Figure 6.4: Experimental setup used to characterize the QPM waveguides. The input source was polarization controlled in free space before coupled into the test samples. The output was fiber butt-coupled and passed through the WDM to isolate the SHG from the fundamental pump, which were measured simultaneously by various detectors and OSA.
an erbium-doped fiber amplifier (PriTel FA-22) and polarization controlled in free space to provide up to 40 mW average power within a 0.1-nm spectral bandwidth. The output was end-coupled into a 775 nm/1550 nm WDM acting as a filter to isolate the SHG from the fundamental with 30-dB isolation. A silicon detector and power meter was used simultaneously to measure the SHG and fundamental powers, respectively, for real-time measurement of the SHG conversion efficiencies. An OSA (Ando AQ6317B) was also used to measure spectral bandwidths as well as verify the wavelength of the SHG. The combined effect of the WDM and silicon detector provided over 100-dB of isolation between the fundamental and the SHG.

To determine the phase-matching period, the dispersion characteristics of the laser written waveguides were estimated using BGW [48] designed around 775 and 1550 nm. Transmission spectra of the BGW yielded a Bragg dip at a center wavelength that was used to calculate the effective index from pre-determined grating periods as shown in a sample set of transmission spectra designed for 1550 nm is shown in Fig. 6.5. By varying the duty cycle of the BGW from 75% to 90%, the effective index was extrapolated to

![Figure 6.5](image_url)

**Figure 6.5:** Transmission spectra for a set of BGW used to estimate the effective index of laser written waveguides at 1550 nm. The central wavelength of the transmission dip was measured for pre-determined grating periods to extrapolate and estimate the effective index of the laser written waveguides of 100% duty cycle. The BGWs were probed with unpolarized light for this estimate as low waveguide birefringence was expected for these laser written waveguides at 1550 nm.
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A uniform waveguide without Bragg modulation. A minimum duty cycle of 75% was selected as waveguides with lower duty cycles suffer from increasingly larger losses due to the extensive gaps between the waveguiding segments, while a linear extrapolation was extracted around the 100% duty cycle of a regular waveguide. A number of chirped QPM periods were then tested for SHG efficiency. Finally, by successively narrowing down the range of the chirped QPM period and by sweeping the fundamental wavelength, the QPM period was obtained for a chosen fundamental wavelength.

The SHG output for the QPM waveguide was measured and found to scale quadratically with input power as shown in Fig. 6.6, confirming the second-order nonlinear process. In addition, the SHG output was also confirmed with the OSA. Furthermore, the polarization-dependent SHG was also investigated using linearly polarized fundamental with its polarization angle rotated with respect to the poling axis while keeping the laser intensity constant. The polarization selection was performed in free space using a com-

![Figure 6.6: SHG output as a function of input power for a QPM waveguide. The output was found to scale quadratically as was expected for this second-order process. The dashed line is a quadratic fit to laser power.](image)
bination of waveplates and a polarizer as shown in Fig. 6.4. The measured power levels were converted into a conversion efficiency in units of 1/W-cm\(^{-2}\) according to:

\[
\eta_{2\omega} = \frac{1}{\sigma_m^2} \frac{I_{2\omega}}{I_{\omega}},
\]

(6.1)

where \(I\) represents the beam intensities calculated from the spatial mode sizes, laser repetition rate, and pulse duration assuming a square temporal profile, and \(\sigma_m\) representing the mode overlap integral between the fundamental and SHG modes according to:

\[
\sigma_m = \frac{\iint (E_{\omega}^2)^* E_{2\omega} dxdy}{\iint (E_{\omega}^2)^* E_{\omega} dxdy \iint (E_{\omega})^* E_{2\omega} dxdy},
\]

(6.2)

where the square of the fundamental mode, \(E_{\omega}^2(x, y)\), for this second order process. Calculating \(\sigma_m\) for the fundamental and SH mode sizes of 12.8 µm \(\times\) 12.4 µm and 6.5 µm \(\times\) 9.7 µm for 1550 nm and 775 nm, respectively, yields a 97.4% mode overlap resulting in a 95% correction to the conversion efficiency due to mode mismatch.

The resulting dependence on the input polarization angle is shown in Fig. 6.7, together with a fit of the data according to the expected polarization dependence [33]:

\[
\eta_{2\omega}(\theta) = A(\cos^4 \theta + \frac{1}{9}\sin^4 \theta + \frac{4}{9}\cos^2 \theta \sin^2 \theta),
\]

(6.3)

where the measured conversion efficiency, \(\eta_{2\omega}(\theta)\), depends on the maximum conversion efficiency, \(A\), and the input polarization angle relative to the internal DC-field, \(\theta\). The observed polarization dependence of the SHG was in excellent agreement to the expected model. The first term of Eq. 6.3 corresponds to type 0 phase matching where both the fundamental and SHG are in the \(\parallel\)-direction, the direction of poling; The second term corresponds to type I phase matching where the fundamental is in the \(\perp\)-direction and the SHG in the \(\parallel\)-direction; The third term represents type II phase-matching where the fundamental consists of equal \(\perp\)- and \(\parallel\)-component and the SHG is in the \(\perp\)-direction. The coefficients before these terms are a result of the intrinsic \(\chi^{(3)}\) tensor geometry [33]. The
observed SHG follows the theoretical $\chi^{(3)}$ response expected for an effective $\chi^{(2)}_{\text{eff}}$ resulting from an internal, frozen-in field within the substrate as in the present experiments.

6.4 QPM Waveguide Response

The previous section showed that a QPM waveguide was successfully fabricated and verified the frequency doubling and polarization dependence. The observed spectral response of this device is characterized and presented in this section. The SHG spectra of a 6.2 mm long waveguide with a 62.5 $\mu$m uniform QPM period obtained with linearly-polarized fundamental input in the $\parallel$- and $\perp$-directions are shown in Fig. 6.8.

The recorded spectra of conversion efficiencies, $\eta_{2\omega}$, was fitted against a modified version of the model presented in Eq. 2.8 for QPM SHG in the non-depleted pump approximation with linear absorption [75,78]:

$$\eta_{2\omega} = \eta_{2\omega}^0 \eta_{\text{PE}} \exp[-(\alpha_{\omega} + \alpha_{2\omega}/2)L]\frac{\sin^2(\Delta k L/2) + \sinh^2[(\alpha_{\omega} - \alpha_{2\omega}/2)L/2]}{(\Delta k L)^2 + [(\alpha_{\omega} - \alpha_{2\omega}/2)L/2]^2}, \quad (6.4)$$
where an additional normalized conversion efficiency term, $\eta_{PE}$, is introduced to provide a first order correction for the presence of random periodicity errors, or variations in the lengths of the domain, which arises from the fabrication process. Assuming a normal distribution for these random errors and $N \gg 1$, $\eta_{PE}$ takes the following form [78]:

$$\eta_{PE} \approx \frac{4}{N\sigma_{\phi}^2} - \left( \frac{8}{N^2\sigma_{\phi}^4} - \frac{1}{6N^2} \right) (1 - e^{-N\sigma_{\phi}^2/2}),$$

(6.5)

where $\sigma_{\phi}^2$ is the variance in the phase error, defined as a function of the coherence length, $L_c$, and the variance in the domain length, $\sigma_l^2$, according to:

$$\sigma_{\phi}^2 = \pi^2 \sigma_l^2 / L_c^2.$$ 

(6.6)

For the QPM waveguide response shown in Fig. 6.8, a fitting curve according to Eq. 6.4 was used to fit the experimental data points yielding a good representation of the experimental data. The figure shows the SHG spectra for a 6.2-mm long QPM waveguide with 62.5 µm QPM period probed with polarization parallel (blue/green) and perpendicular (red/turquoise) to the poling field. Points are experimental data and lines are theoretical models (Eq. 6.4).

**Figure 6.8:** SHG spectra for a 6.2-mm long QPM waveguide with 62.5 µm QPM period probed with polarization parallel (blue/green) and perpendicular (red/turquoise) to the poling field. Points are experimental data and lines are theoretical models (Eq. 6.4).
with the following values for maximum conversion efficiency of \(4.8 \times 10^{-16}/\text{W-cm}^{-2}\) at 1536.6 nm and a phase-matching bandwidth of 4.4 nm. For the \(\perp\)-polarization, the peak efficiency of \(8.8 \times 10^{-17}/\text{W-cm}^{-2}\) calculated at 1537.5 nm was weaker as expected and slightly shifted spectrally by \(\sim 0.9\) nm compared to the \(\parallel\)-polarization, which is attributed to the slight birefringence of the laser formed waveguide [95].

The spectra for the chirped QPM waveguides were compared with the non-chirped, uniform QPM waveguide upon normalization by conversion efficiency and phase-matching wavelength in Fig. 6.9. A wider fundamental phase-matching bandwidth (FWHM) of 9.4 nm and 8.9 nm was observed for 0.38 and 0.55 \(\mu\)m/mm chirped waveguides, respectively, despite being longer than the uniform period device, which has a narrower 4.4 nm bandwidth. Typically, a longer sample results in a reduced bandwidth [75], and a corresponding \(\sim 2\) nm bandwidth is expected for an 18 mm long, uniform QPM sample. The observed 9.4 nm bandwidth represents an approximately \(5\times\) wider bandwidth due to the 0.55 \(\mu\)m/mm chirping of the QPM period, demonstrating a clear increase in phase-matching bandwidth due to QPM chirping. In addition, the theoretical sinc\(^2\) spectrum for the 6.2 mm, uniform period (dashed black line) is also presented to illustrate the slightly broadened spectra of the physical device due to waveguide losses and potential fabrication inconsistencies. The ability and flexibility to chirp or to make aperiodic QPM structures using direct laser writing make this technique promising for achieving advanced nonlinear processes and functions with a bulk glass silica photonics platform [97, 98].

Further analysis of the length dependence of SHG was conducted by a cut back method, cleaving a QPM SHG waveguide into shorter lengths. The maximum SHG conversion efficiency was measured for each length and plotted in Fig. 6.10. A model based on Eqs. 6.4-6.6 using known device parameters (such as pump power, waveguide length and loss, QPM period) was used to obtain the green fitting curve with unknown parameters (such as \(\chi^{(2)}_{\text{eff}}\) and variance of the QPM period) in Fig. 6.10 as fitting parameters.
6.4. QPM Waveguide Response

Figure 6.9: Comparison of uniform and chirped QPM waveguides after being aligned to their central wavelength and normalized for conversion efficiency. The circles represent measured data points and the dashed lines represent a fit for the measured points of the same colour. The phase-matching bandwidth was approximately 5\times wider for the chirped QPM waveguides as compared to the expected, experimental uniform period waveguide of the same length. The black dashed line represents the theoretical $\text{sinc}^2$ spectrum for the uniform, 6.2 mm sample to illustrate the broadening effects of loss and fabrication inconsistencies present in these physical devices.

The measured SHG conversion efficiencies fit well against the model in Eq. 6.5 for a random periodicity standard deviation error of 3.3 $\mu$m, which roughly represents 5.2\% for a 62.5 $\mu$m period. Physically, this estimate of random periodicity error likely encompasses a wider range of fabrication variations including local variations in poling depth and effectiveness, and overlap between the waveguide and induced nonlinearity. A comparison is made against a model without period variations (green) in Fig. 6.10, indicating that random periodicity variation is the largest limiting factor for SHG. The effect of this random error may be caused by a combination of fabrication variations in the waveguide writing, poling and erasure processes, which also causes large variations in device performance,
Figure 6.10: SHG conversion efficiencies measured for various lengths created from a single device using the cutback method. The results fit well against the SHG model (blue) with propagation losses of 1.3 dB/cm and 6.7 dB/cm for 1550 nm and 775 nm, respectively, and for a random periodicity standard deviation error of 3.3 µm, or 5.2% for a 62.5 µm period, which encompasses local fabrication variations in the thermal poling process. A comparison is made against the expected conversion efficiency for the absence of period variations case (green), lossless case (purple), and ideal, optimized case (black) with low propagation losses of 0.5 dB/cm and 1.0 dB/cm for 1550 nm and 775 nm, respectively, to illustrate the relative limitations of these processes.

which when improved, will enable reliable comparisons between different fabrication conditions such as between single and double poled waveguides. Non-uniform writing and poling may cause slight local variation in the dispersion properties of the waveguides. Variations across the 4.0 µm erasure track created by the ∼1.5 µm diameter laser beam may result in inconsistencies in the period boundaries. This could be optimized in the future by increasing the resolution of the 4.0 µm erasure beam by reducing the pulse energy and increasing the number of erasure tracks to ensure greater erasure uniformity. The effect of propagation loss is also shown in Fig. 6.10 by contrast against the model without losses (green), which limits the SHG efficiency for longer device lengths. In addition, there is also a mode mismatch (49% on one mode field diameter (MFD) dimension) between the guiding modes of these two wavelengths (Fig. 6.3) that was not accounted
for in the models. The SHG mode is expected to follow the distribution of the fundamental mode, which would experience greater loss than an already well-coupled mode. The combined presence of both length-limiting factors predicts an optimal waveguide length of 10.2 mm, after which the total conversion efficiency is expected to decrease.

After careful polarization optimization, a highest peak SH efficiency of $6.2 \pm 0.5 \times 10^{-6} \%$, or $1.3 \pm 0.1 \times 10^{-15}/\text{W-cm}^{-2}$ was measured at 1542.8 nm for a 10.0 mm long device. An effective SON of $\chi^{(2)} = 0.013 \pm 0.002 \text{ pm/V}$ was calculated for this device from Eq. 2.8 and the known input source parameters of 500 ps pulse duration and 1 MHz repetition rate for the tunable fiber laser. For a shorter 2.5 mm device, a maximum effective SON, $\chi^{(2)} = 0.020 \pm 0.002 \text{ pm/V}$ was achieved. The larger effective $\chi^{(2)}$ measured for the shorter sample was due to the reduced sensitivity to fabrication variations for the shorter device. While very low compared to the nonlinearity of lithium niobate ($\sim 21 \text{ pm/V}$ [99]), this value of $\chi^{(2)}$ is similar to those reported in QPM poled silica fibers [100]. A non-uniform nonlinearity across the sample during the poling process would result in a lower average effective $\chi^{(2)}$. By exploring different laser processing conditions, the modes could be designed to overlap better while improving losses. The SHG propagation and scattering losses due to the mode mismatch between the fundamental and SHG modes during the conversion process could also be improved to attain low propagation loss waveguides limited to 0.5 dB/cm and 1.0 dB/cm for 1550 nm and 775 nm, respectively. For such an optimized device with more uniform poling and erasure, the conversion efficiency can be improved by nearly four orders of magnitude to $1.0 \times 10^{-11}/\text{W-cm}^{-2}$ for the same 10.0 mm long device, and up to $6.7 \times 10^{-11}/\text{W-cm}^{-2}$ for a 58 mm long device.

The center of the waveguide mode is currently positioned near the edge of the induced nonlinearity region, which could be better overlapped by writing the waveguide from the opposite surface of the glass substrate to waveguides closer to the surface. Varying poling time and poling voltage during the thermal poling process could also be used to increase the depletion depth. Finally, grinding techniques can be applied to more accurately
position the nonlinearity across the waveguide [64] for future enhancement. The result of a more effective nonlinear overlap could improve the SON by nearly two orders of magnitude toward the \( \sim 1 \text{ pm/V} \) achievable in fused silica [30], representing an additional four orders of magnitude improvement in conversion efficiency up to \( \sim 10^{-6}/\text{W-cm}^{-2} \). Finally, the erasure process could be further optimized and the QPM period tailored to the pump bandwidth to improve conversion efficiency for longer lengths.

### 6.5 Summary

An integrated fabrication process was developed to successfully generate SHG in a femtosecond laser written QPM waveguide in fused silica, which involved thermal poling, femtosecond laser writing and erasure for QPM. Chirped QPM was used to narrow down to the correct phase-matching period of 62.5 mm for the femtosecond laser waveguides. A maximum conversion efficiency of \( 1.3 \pm 0.1 \times 10^{-15}/\text{W-cm}^{-2} \) was achieved as well as an effective SON of \( \chi^{(2)} = 0.020 \pm 0.002 \text{ pm/V} \) at a similar nonlinearity to existing poled fiber demonstrations. These results demonstrate the first step and feasibility of creating nonlinear components for future integrated lab-on-a-chip applications to further enhance the suite of femtosecond laser written devices.
Chapter 7

Summary and Future Work

7.1 Summary

Femtosecond laser processing is a versatile, three-dimensional (3D) fabrication technique for creating integrated optical devices in fused silica that was further developed and advanced in this study through the demonstration of linear and nonlinear, 3D integrated photonic devices. Starting with linear optical functions, waveguides and directional couplers were designed and optimized in Chapter 4 as building blocks for more complex devices such as Mach-Zehnder interferometers (MZIs) and interleavers. A key result from a few years earlier was the flat-top interleaver (FTI) and spectra in Fig. 4.7, which has since seen further development in silicon photonics to yield lower crosstalk below -24 dB [102] with narrower channel spacing in a much more compact size on the order of tens of microns [103]. Nevertheless, the significance of the present work was the demonstration of robust control through the precise modeling of individual components by the matrix transforms that underlies the reliable scaling for the design and optimization of an integrated device. The benefit of direct, maskless femtosecond laser writing enables an iterative design and optimization process through rapid prototyping of desired spectral characteristics as individual waveguides were written in a matter of minutes, made possible by sufficient process accuracy and fabrication consistency that
had been demonstrated. Going forward, more complex devices can be designed and integrated, for example, with buried, 3D microfluidic channels, which has been integrated with simple waveguide structures in a wide variety of growing biochemical and sensor applications [58, 104, 105].

In addition, quantum communication is another promising avenue for femtosecond laser written devices for monolithically integrating multiple components into a single chip to ensure relative phase stability among each component while buried within an isolated glass substrate. Though less dense and compact than the circuits achievable through silicon photonics, femtosecond laser written circuits can once again be rapidly prototyped to test a range of quantum photonic devices and concepts while benefiting from low coupling losses to fiber, which allows for a high photon extraction efficiency [7].

As femtosecond laser development is extended to nonlinear devices, various poling conditions were studied in Chapter 5 using second-harmonic (SH) microscopy to visualize and infer the physical processes underlying the interaction between thermal poling and femtosecond laser writing. A SH microscopy system and probing technique was developed and built in order to monitor the poling zone around the waveguide region with \( \sim 1 \mu m \) resolution. This system was designed to ”self-analyze” the photonic devices previously fabricated by the same femtosecond laser writing system. In addition to eliminating the need for a separate characterization systems, having the same setup available allows for consistent alignment of samples between the fabrication and characterization steps, as calibration errors and offsets would be consistent under both modes of operation. The spatial travel range available for characterization would also be sufficient for any fabricated device, since the same translation stages are used. Overall, the development of this SH microscopy system is a novel extension of femtosecond laser processing, further demonstrating the versatility of this technique.

The SH microscopy system developed in this thesis was used to observe the waveguide blocking and erasure effects present in thermal poling, with the result presented in
7.1. Summary

Fig. 5.2. This observation led to the idea and the development of a new double poling method to overcome the previous challenges to inducing an effective second-order nonlinearity (SON) within femtosecond laser written waveguides in fused silica as shown in Fig. 5.4. As a result, second-harmonic generation (SHG) was demonstrated in Chapter 6 in a quasi-phase-matched (QPM) femtosecond laser written waveguide as the first demonstration of an ideally phase-matched, standalone, all-femtosecond laser written nonlinear device through the utilization of this new poling process with the result shown in Fig. 6.8. The versatility of femtosecond laser writing was also evidenced by the development of a new femtosecond laser based erasure technique to perform the QPM for nonlinear frequency conversion. Chirped nonlinear gratings were created to demonstrate the flexibility of this erasure technique and as part of an efficient, maskless process for achieving perfect phase-matching, which also relies on the rapid prototyping capabilities of direct femtosecond laser writing.

Though this initial demonstration of the QPM waveguide only yielded a conversion efficiency of 6.6 ± 0.8 × 10^{-5} %/W, an optimized SHG device response was modelled and estimated to provide four orders of magnitude improvement mainly through simply optimizing propagation losses. An additional two orders of magnitude is expected by improving the poling and physical overlap between the nonlinear region with the waveguide to more closely capture the full ∼1 pm/V nonlinearity available in bulk fused silica [30], and thereby promise a much stronger conversion efficiency of ∼300 %/W for a 58 mm long device, which approaches the ∼500 %/W value previously observed for QPM lithium niobate [101]. The additional benefit for achieving similar conversion efficiencies is both the low substrate cost and ease of integration into a lab-on-a-chip devices, which may be integrated with components such as microfluidic channels. Extending once again to quantum applications, additional nonlinear components that were traditionally outside of the photonic circuit could also be designed and monolithically integrated to include the SHG and spontaneous parametric down-conversion (SPDC) components to directly
generate entangled photon pairs within the circuit for greater stability across a larger proportion of the quantum setup currently used for quantum experiments [17, 106].

The work presented in this thesis extends the capabilities of femtosecond laser processing, both by demonstrating the feasibility of complex device integration and also by opening an entire avenue for developing nonlinear applications in fused silica. The foundations developed in this thesis will enable further research and development as femtosecond laser processing takes on an increasingly larger role in creating future lab-on-a-chip and lab-on-a-fiber devices with comprehensive passive and nonlinear functions integrated seamlessly together as the next frontier.

7.2 Future Work

The combination of linear optical components with the recent demonstration of nonlinear functionality lays the foundation for the advanced design and control of novel integrated circuits using femtosecond laser processing in fused silica. Three distinct avenues for future work is proposed: (1) Building out the suite of nonlinear devices and applications in fused silica, (2) integrating microchannels to induce SON in novel 3D geometries and patterns by leveraging the intrinsic 3D capabilities of femtosecond laser writing, and (3) designing nonlinear circuits in fused silica fiber.

Other nonlinear processes can be pursued with femtosecond laser writing to create new applications for quantum communication and quantum cryptography. By using the newly developed femtosecond laser erasure technique, waveguides can be phase-matched to other nonlinear processes, such as SPDC, which can be used to monolithically generate entangled photons. Directional couplers (DCs) could also be potentially used to manipulate, isolate, or combine various signals.

Microchannels can be arbitrarily formed within fused silica in various flexible geometries, which could be used to form microchannel electrodes within fused silica. With these arbitrary electrodes, the induced nonlinearity from thermal poling could be designed to
generate arbitrary 3D patterns to match electric field patterns. Helical microchannels could potentially lead to a more effective QPM technique without the need for a separate erasure process, which would allow the nonlinear signal to grow throughout the entire interaction length.

Nonlinear optical circuits can also be transferred from bulk fused silica onto optical fiber as femtosecond laser processing has begun to move into fiber, with an example of optical resonator arrays being developed within fiber [59]. Newly established thermal poling and SH characterization techniques applied to fiber would allow for longer interaction lengths and flexible devices that can be easily spliced into existing fiber systems. Nonlinear lab-on-a-chip applications can be developed into lab-in-a-fiber applications.

Overall, femtosecond laser writing of linear and nonlinear optical devices will continue to be an active and growing field of research as 3D nonlinear optical circuits can be contemplated for a widening range of new application directions.
Appendix A

Electrode Formation

This appendix summarizes the background preparation work performed in developing various designs of electrodes for thermal poling, which were designed to direct the high voltage fields into the optical devices within glass in novel 3D geometries. Various methods involving surface wires and microchannel electrodes are described in the following subsections. These methods could be used as a foundation for developing future nonlinear circuit geometries.

A.1 Surface Wire Electrode

A surface wire electrode configuration consisted of fixing a thin, 25 µm tungsten wire anode across the surface of the glass substrate that rested on top of a strip heater, which also acted as the cathode, as shown in Fig. A.1. The waveguide characterization stages were used to stretch and clamp down the thin metal wire across the glass substrate before being fixing down with epoxy. Small metal alligator clamps were used to connect the wires with the high voltage circuit described in Section 3.3. For this configuration, waveguides were written within 14 µm from the surface in order to maintain close proximity to the anode. Though simple to fabricate, any nonlinearity induced was restricted to the region just below the surface.
A.2 Buried Wire Electrode

Microchannel electrodes were fabricated by modelling the design of twin-holed fiber. Buried microchannels with roughly 50 µm diameters were chemically etched parallel alongside a buried waveguide at separation distances between 5-10 µm. The microchannels opened to the surface on either end of the substrate to maximize the potential interaction length. Thin wire electrodes were then carefully inserted into the buried channels before connected to the high voltage circuit in a similar manner as with the thin wire electrodes, with the wire acting as the anode, and the heater strip below acting as the cathode. A schematic and microscope image of the microchannel design with inserted thin wire electrode is shown in Fig. A.2. The buried microchannel is exposed to the surface at either end with a 200 µm×100 µm wide opening to allow insertion of the thin wire. This buried microchannel electrode design allowed waveguides to be written deeper within the substrate to reduce the scattering loss caused by being near the surface.
Figure A.2: Depiction of a buried wire electrode. (a) Schematic of thin wire inserted into a buried microchannel beside a MZI. (b) Microscope image of a thin wire inserted inside a buried microchannel.

A.3 Silver-Coated Microchannel Electrodes

Silver-coated microchannel electrodes take advantage of the 3D capabilities of femtosecond laser processing and a variety of geometries can be designed to control the orientation of electric fields during thermal poling. To form these microchannel electrodes, buried microchannels were first formed similar to those in the buried wire electrode design. A syringe was used to mechanically pull the silver plating solutions, consisting first of a dextrose solution and then a silver nitrate solution, through the microchannels to form a silver layer along the walls. The ingredients used to make these two solutions are detailed in Table A.1 [107]. In this way, parallel electrodes were formed beside or underneath laser written waveguides at various distances. Microscope transmission images of a silvered buried microchannel spaced 4 µm away from a laser written waveguide is shown in Fig. A.3. The 50 µm diameter microchannel is shown before and after silver plating.
A.3. Silver-Coated Microchannel Electrodes

Table A.1: Ingredients for the silver plating solutions

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Concentration (Quantity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver Nitrate Solution</td>
<td></td>
</tr>
<tr>
<td>Silver nitrate (AgNO₃)</td>
<td>0.10 M (30 mL)</td>
</tr>
<tr>
<td>Ammonia (NH₃)</td>
<td>15 M (Dropwise until precipitate dissolves)</td>
</tr>
<tr>
<td>Potassium hydroxide (KOH)</td>
<td>0.80 M (15 mL)</td>
</tr>
<tr>
<td>Dextrose Solution</td>
<td></td>
</tr>
<tr>
<td>Dextrose (C₆H₁₂O₆)</td>
<td>0.25M (3 mL)</td>
</tr>
</tbody>
</table>

Figure A.3: Microchannel fabricated 4 µm away from laser written waveguide before (left) and after (right) silver plating.

In addition, helical microchannels were formed using a multi-stage process where the laser exposure for the waveguide and helical microchannels were written over multiple steps. Afterwards, the samples were etched with hydrofluoric (HF) acid before being coated with the silver plating solution. This formed a helical pair of conductors around the waveguide, which were explored as a potential avenue for reversing poling domains for QPM. Smooth, buried, helical microchannels with a period of 300 µm is shown on the left side of Fig. A.4 before silver plating. Helical microchannels with a tighter 100 µm period are shown on the right side of Fig. A.4 after silver plating. In this right image, the HF had leaked through into the waveguide during the chemical etching process, exposing the waveguide.
Figure A.4: Photographs of helical microchannel electrodes. (Left) Helical microchannels around a waveguide before silver plating. (Right) Helical microchannels after silver plating, where the waveguide had been etched and plated during the chemical etching process.
Bibliography


